CHILLING OF BROILER CARCASSES: MICROBIOLOGICAL AND QUALITY IMPLICATIONS

by

ROGER IVAN HUEZO

(Under the Direction of Julie K. Northcutt)

ABSTRACT

Three studies were conducted to evaluate the effects of chilling method on bacteria recovery, carcass quality, meat functionality and meat quality. In all three studies, carcasses were cooled by dry air (3.5 m/s, -1.1^{o} C, 150 min) or by immersion chilling in ice water (0.6^{o} C, 50 min). Results showed that air and immersion chilling, without any chemical intervention, are microbiologically equivalent. Carcass bacterial reductions of up to 1 log units were obtained for *E. coli*, coliforms, and *Campylobacter* using either air or immersion chilling. Chilling method had no effect on *Campylobacter* or *Salmonella* prevalence. However, chilling method has an effect on carcass skin appearance and yield. Color, pH and texture of broiler breast fillets harvested at the same postmortem time were similar for air and immersion chilled carcasses. Fillet functionality was improved by air chilling (higher cook yield), but the lower cook yield of immersion chilled fillets resulted from the high moisture absorption during submersion in the chiller water. Air chilling has an effect on rigor mortis, but post-chill aging time is always required to maximize the proportion of tender meat.

INDEX WORDS: poultry, immersion chilling, air chilling, aging time, poultry meat color, tenderness, carcass contamination, carcass microbiology

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INTRODUCTION

The main purpose of chilling is to reduce carcass temperature below the minimum growth temperature of most foodborne pathogens and spoilage microorganisms. The United States Department of Agriculture (USDA) requires that poultry carcasses be chilled to 4º C or lower in 4, 6 or 8 hours for carcasses weighing less than 4 pounds, 4-8 pounds, and more than 8 pounds, respectively [1]. Regulations in Europe require a final temperature of 4º C for poultry carcasses but there are no time requirements [2]. In both cases, internal temperature should be measured on the thickest section of the breast, because it has been identified as the portion of the chicken carcass to cool at the slowest rate [3].

Poultry chilling systems may involve a variety of coolants such as water, air, solid carbon dioxide or liquid nitrogen. Before 1978, immersion systems using water as a coolant were the most widely used chilling method because of efficiency and low cost. At that time, water-immersion chillers were operated primarily to increase carcass yield, and in many instances improper procedures (low overflow, high organic material, and parallel flow) led to an increase in the microbial load in the chilling water and caused carcass cross-contamination [4]. In the late 70's, a ban on "spin chilling" or auger chilling was implemented in the European Union (EU) because of the unsatisfactory hygiene conditions and excessive water uptake in commercially processed carcasses [5]. This ban resulted in an extensive amount of research to develop commercial alternatives to immersion chilling of poultry carcasses in order to accommodate European Community objections. This research resulted in two additional methods for cooling poultry carcasses: air and evaporative chilling [6].

In the U.S., immersion chilling has traditionally been the most common method of cooling poultry because it is both efficient, economical and easy to accomplish [7, 8]. However, air chilling is gaining in popularity because of limited availability of water, strict wastewater discharge restrictions, increasing concerns over cross-contamination, and new federal regulations on carcass moisture retention [1]. In addition, air chilled poultry may be exported to countries in the European Union (EU) where immersion chilled poultry is prohibited [2, 5, 9].

A significant amount of research on poultry immersion chilling has been published, while the information on air chilling is limited. Few studies have compared air and immersion chilling systems. Therefore, the purpose of the present study was to evaluate the effects of chilling method on carcass bacteria levels, carcass quality, and breast fillet functionality and quality.

LITERATURE REVIEW

Immersion chilling of carcasses:

Immersion chilling of poultry carcasses in cold water or ice-water mix has been practiced since 1910 [10]. In general, the time to reach a deep breast muscle temperature below 4 ^{o}C is approximately 30 to 50 minutes [6, 10]. Immersion chilling systems may be classified as batch or continuous-flow. Batch systems ("static" or "slush-ice chillers") were quickly considered impractical in large-scale operations due to excessive labor, handling, and because these systems can not support a continuous production rate [11]. The continuous-flow immersion chillers ("mechanical chillers") provide a continuous forward motion of the carcasses, with chilling rates that are 2-6 times faster than static chillers. However, the moisture absorption with these systems is also higher [11]. Continuous immersion chilling usually involves multiple stage tanks. Carcasses are removed from the shackle and slowly pushed through the water by rotated paddles, rakes or augers. In the first chilling stage, usually called "pre-chiller", the water temperature is about 7º C to 13º C and dwell time is approximately 10 to 15 min [12]. At the entrance of the pre-chiller, the carcass temperature is about 40º C, but carcass temperature is reduced to 25 to 30º C prior to entering the main chilling tank [12].

The final chilling stage typically includes two different systems – parallel and counter flow. Parallel-flow immersion chilling ("spin-chilling") occurs when the water runs in the same direction as the carcasses, and the carcasses are slowly moved along the tank by the action of a paddle-type agitator. In this system, the water absorption is high but less uniform. Counter-flow immersion chillers are currently the most widely used chiller system in the poultry industry. In this system, the flow of the chilling water runs opposite to the flow of the carcasses so that the

carcasses are chilled in increasingly clean and colder water. The counter current flow maximizes the heat exchange from carcasses to water and enhances the cleanliness of carcasses. Multiple tank countercurrent chiller systems are designed in such a way that the overflow from an upstream tank is discharged into the previous tank to recycle the refrigeration energy [7, 11-14]. The temperature of the water is controlled by the application of crushed ice, typically added from an overhead hopper to the entrance of the chiller, or by heat exchange of recycled water. The amount of ice needed to cool the carcass from 37.8º C to 1º C is 0.38 kg of ice per kg of meat, but typically from 0.4 to 1 kg is used in the industry [15]. The use of crushed ice has been largely replaced by cold water obtained directly from a heat exchange unit [16]. After the water has been used to cool the carcass, it is cooled again to 33º F to 35º F and reused in the chilling process. This reused chiller water is commonly referred as “red water”.

During the chilling process, the water not only extracts heat but also removes solids (skin, fat, etc.) including microorganisms from the carcass [17, 18]. To control the level of contamination, regulations mandate the continuous incorporation of potable water to maintain an overflow rate of 1.89 L/ bird or greater in the US [1]. In the EU, the water overflow requirements are 2.5, 4.0, and 6.0 L/bird for carcasses weighing less than 2.5 kg, 2.5 to 5 kg, and more than 5 kg, respectively [2]. Also, regulations in many countries outside the EU allow the use chlorine to prevent cross contamination.

During immersion chilling, the heat transfer coefficient is high. Mechanical agitation of water and air injection are the usual means to prevents the formation of a thermal layering at the product surface. This layer thermal insulates the surface and reduces the heat exchange [12, 16]. Agitation of the bird during chilling increases moisture absorption as water pockets form beneath the skin. Moisture absorption is greatest in carcasses with a high degree of exposed flesh. During

immersion chilling, the average water uptake is about 4 to 8%, but the difference between individual carcasses is extremely high with a coefficient of variation between 25 and 45% [10, 19].

Air chilling:

Air chilled carcasses pass through a cold room or air tunnel (air temperatures from -7º C to 2º C) on the shackle line for 90 to 150 min [8, 12]. Air chilling of poultry carcasses has been used extensively in EU countries, where carcasses are typically soft-scalded and sold fresh. Soft scalded poultry (49.4 – 52.2^{o} C) still retains the cuticle which serves to protect skin from dehydration from cold air [10]. Air chilling may involve a pre-chill stage for one hour at 5º C to remove moisture from the carcass, and a final chilling stage for 1.5 hours at 0º C. These two chilling stages cool the carcass to a temperature of 1º C [7, 20]. In air chilling, air velocity has almost as much effect as the air temperature. Freezing rate increases rapidly as air velocity increases from 0 to 4 m/sec. Above 6 m/s, the effect of air velocity on carcass temperature is almost negligible [15].

There are technological differences in the application of air chilling system. Cold air may be blown either down into the carcass or across the carcasses. These systems are known as “downflow” or “crossflow” air chilling. Some systems have ducts which blow the cold air directly into the carcass body cavity and over the thickest part of the breast to increase chilling efficiency [21]. In general, the weight loss by evaporation of water in commercial air chilling operations is at least 1 to 1.5%, but loss can increase to as much as 3% in poorly designed equipment [10, 22].

Evaporative chilling (spray chilling):

Evaporative chilling is an alternative air system frequently used for hard-scalded carcasses. The process is carried out by periodically spraying carcasses with water as cold air is blown into or across the carcasses. It has been reported that spraying carcasses during air chilling improves the heat transfer due to evaporation. Carcass weight after evaporative chilling is comparable to the pre-chill weight, and no discoloration occurs [10]. Typically the chilling time is less than 90 minutes [8], and the water consumption is less than 0.1 L per carcass for each series of spray nozzles [7].

During evaporative chilling, the rate of evaporation is kept as high as possible by spraying the carcasses periodically to maintain maximum water activity on the surface of the birds. Thus, no water is removed from the inner part of the meat and no dehydration of the product occurs [7]. In a conventional dry air chilling, the carcass surface is sufficiently wet at the beginning of the process, but becomes dry during cooling. Water vapor filters through the tissue, and the rate of evaporation is slowed down [23]. The total heat transfer from the product to the circulating air can be divided into two parts - the heat loss due to temperature difference, and the heat loss due to evaporation of water from the surface [22]. When the water activity of the carcass surface is close to 1 and the surface temperature approaches the air temperature, nearly all heat transfer is due to evaporation of water from the surface of the bird [22].

Klose [24] evaluated evaporative/vacuum chilling of carcasses and found that the chilling rate was comparable to immersion chilling, but weight losses were as high as 5% of the pre-chill carcass weight. Experimental work has been published on spray chilling of poultry using only cold water (without air), but the high volumes of chilled water required to cool the carcasses makes this system economically and environmentally unacceptable. Some poultry equipment

companies offer in-line immersion-evaporation systems where birds are immersed in one or two stage counter current immersion chillers, and then are passed through a down flow air chiller. This system is reported to reduce the moisture absorption compared to immersion chilling and to improve the appearance and microbiological quality of the final product [25]; however, there is no scientific documentation to support this claim.

Effects of chilling method on carcass microbiology:

Unlike parallel-flow chillers, counter-flow immersion chillers efficiently reduce carcass bacterial numbers because carcasses are constantly moved toward cleaner water [13, 14]. In a microbiological evaluation of a countercurrent immersion chilling, water and carcasses from the chiller had significantly lower total aerobic bacteria (aerobes) and coliforms levels compared to carcasses and in water from the pre-chiller [26]. Mead and Thomas [27] immersion chilled chicken carcasses using 2.5 L/carcass in a three unit counter-flow chiller, and reported a difference of 1 log cfu/mL between the carcasses in the first chiller and the carcasses in the last chiller. Carcasses in the second chiller were at an intermediate level of contamination. These data showed a washing effect as carcasses passed through the system. In this same study [27], the effect of immersion water volume on carcass bacterial contamination was evaluated. A difference of 1.2 and 0.5 log cfu/mL for aerobic counts and coli-aerogenes bacteria, respectively, was found when the water volume was increased from 2.5 L/carcass to 5 L/carcass. Mulder *et al.* [19] reported a small difference in the microbiological quality between carcasses chilled with 1.5 and 2.5 L/carcass. These two studies were performed in a commercial facility where the dwell times were 45 and 30 min respectively. They also used counter-current and air agitation, and these factors could mask the real effect of water volume.

Northcutt *et al.* [28] evaluated the effect of carcass chiller volume in a experimental chiller unit using half carcasses individually cooled in sealed bags containing either 2.1 L/kg (low) or 16.8 L/kg (high) of distilled water. They concluded that a higher volume of water will remove more bacteria from the carcasses during immersion chilling because of the washing effects of the water. They also reported differences in post-chill carcass bacteria counts of 0.5, 0.8, 1.0 and 0.3 log CFU/mL for total aerobic bacteria, *E. coli*, *Enterobacteriaceae* and *Campylobacter*, respectively. Northcutt *et al.* [28] found a lower incidence of *Enterobacteriaceae* (22/24 versus 17/24) and *Campylobacter* (21/24 versus 15/24) after using a higher volume of water compared to a lower volume of water during immersion chilling. When the study was repeated using 3.3 or 6.7 L/kg, no difference was found in the numbers of total aerobic bacteria, *E. coli*, *Enterobacteriaceae* and *Campylobacter* recovered from carcasses [29]. Northcutt *et al.* [29] postulated that doubling the volume of chill water would remove twice as much bacteria from carcasses; however, these differences would not be statistically significant after Log transformation. Data from their second study confirmed this hypothesis [29].

Dickens and Cox [30] evaluated the effect of air injection during chilling on microbiological quality. Air injection had no effect on aerobic plate counts (aerobes) and Enterobactericeae recovery from carcasses, but a significant reduction in *Salmonella* prevalence (80% vs 22%) was observed with air injection. These researchers reported that air injection was more effective in reducing *Salmonella* when applied to inoculated carcasses containing fewer than 150 cells of the marker organism (10% incidence) as compared to levels recovered from inoculated carcasses containing more than 150 cells (35% incidence). The same trend was observed with the water control (70% positive with less than 150 cells; and 90% positive with

more than 150 cells) [30]. The mechanical action of the air injection rinses off *Salmonella* from the carcass, reducing the probability of bacteria recovery.

Many studies have been carried out on the effect of chilling on numbers and prevalence of pathogens recovered from chicken carcasses (Table 1). Both immersion chilling and air chilling have been found to have a minimal effect in reducing the incidence of *Salmonella* on poultry carcasses. Immersion chilling may physically remove some cells by washing, but this is offset by cross contamination between carcasses. Unlike immersion chilling, air chilling does not have a washing effect, but reduces cross contamination between carcasses.

During immersion chilling, numbers of *Salmonella* on carcasses may decrease but more carcasses may become *Salmonella*-positive due to cross-contamination [31, 32]. Chiller water may transport pathogens from contaminated carcasses to 'clean' carcasses [13, 33-37]. Table 1 shows *Salmonella* and *Campylobacter* incidence and numbers recovered from chicken carcasses before and after air or immersion chilling. Despite the fact that immersion chilling may lead to cross-contamination [13, 38-42], it removes *Campylobacter* from the surface of the carcasses, thus reducing the overall persistence [32, 40, 42-50]. For air chilling, results have shown either no microbiological reductions [51, 52], or a slightly lower post-chill *Campylobacter* numbers [45, 46].

Campylobacter incidence is not affected by air chilling [38, 46, 53, 54]. Oosterom *et al.* [55] showed that *Campylobacter* is very sensitive to drying and can not survive on dry surfaces. In air chilling experiments using pig skin with and without forced air, these researchers found that decreased temperatures did not have a significant effect on *Campylobacter* levels, but when forced air was incorporated, the drying effect was a decisive factor for *Campylobacter* recovery. During air chilling of poultry, the skin surface is more moist and drying does not appear to play

as important of a role in destroying *Campylobacter* as it does for porcine. Other reasons for these differences could be the relative short time required to cool chicken carcasses, and the surface of the skin and cavities of poultry carcasses where *Campylobacter* may be protected against the influence of the drying [55, 56]. Chantarapanont *et al.* [57], using direct microscopic observations, showed *Campylobacter* cells adhering to the carcass were located primarily on rough areas of the chicken skin, in crevices or entrapped inside deep channels and feather follicles. Bacteria in skin crevices and follicles may be protected against chemical disinfectants and physical stressors (drying, temperature) and would be more difficult to remove because of capillary action and irreversible attachment to the skin tissue [57].

Table 2 shows the numbers of total aerobic bacteria (aerobes), coliforms, *E. coli*, *Enterobacteriaceae*, psychrotrophic bacteria, and *Pseudomonas* recovered from carcasses before and after chilling. During air chilling, either minimal or no change has been reported for total aerobic bacteria [51, 52, 58-61]. Immersion chilling improves the overall hygienic conditions of freshly eviscerated poultry carcasses with a median reduction of 0.60 $\log_{10}$ CFU for total aerobic bacteria [26, 27, 35, 47, 48, 60, 62, 63]. Graw *et al.*, [59], investigated the effect of evaporative chilling on carcass contamination, and reported 0.44 and 0.55 log CFU/g reduction for total aerobic bacteria, and 0.46 and 0.56 log CFU/g reductions in *Enterobacteriaceae* counts.

Table 2 shows a median reduction of 0.6, 1.1, and 0.7 log CFU for coliforms, *E. coli*, and *Enterobacteriaceae*, respectively, after immersion chilling of poultry carcasses [19, 26, 27, 32, 35, 45, 47, 60, 62-64]. In studies involving air chilling, no significant effect in coliforms, *E. coli*, and *Enterobacteriaceae* has been reported [45, 51, 52, 58-61, 65-67].

Mead *et al.* [68] evaluated cross-contamination during chilling using a high concentration (10^8 CFU/mL) of *Escherichia coli* K12 as a marker organism applied to contaminated carcasses.

These researchers showed that non-chlorinated water chilling resulted in contamination of adjacent carcasses (19/27) with low counts that ranged from 0.4 to 1.1 $\log_{10}$ CFU/mL. Inoculated carcasses had levels that ranged from 3.6 to 4.5 $\log_{10}$ CFU/mL. Presence of *Salmonella* [13, 35, 36, 69] and *Campylobacter* [13, 39, 45, 70] in chiller water samples highlight the risk of cross-contamination during immersion chilling.

In a different study with the same marker strain, Mead *et al.* [71] evaluated cross-contamination during air chilling, and found that the marker bacteria were dispersed in all directions from a single inoculated carcass and the transmission was increased by the use of chlorinated water sprays. They suggested that air-currents, aerosols and water droplets played an important role in cross contamination during air chilling [71]. Ellerbroek [72] reported total aerobic bacteria numbers of 3.28 and 4.16 $\log_{10}$ CFU/m^3 in air inside of an air chilling room and inside a spray chilling room, respectively. The levels of Enterobactereaceae for the same chilling rooms were 2.02 and 2.06 $\log_{10}$ CFU/m^3, respectively [72]. Fries and Graw [73] worked on a baseline study in two processing plant and found total aerobic bacteria numbers of 3.5 and 5.33 log CFU/mL, *Pseudomonas* counts of 2.06 and 4.86 log CFU/mL, and 9/16 *Enterobactereacae* positive samples in aerosols from a evaporative chiller. They also reported 2.55 and 3.17 $\log_{10}$ CFU/m^3 in air inside of air chilling rooms [73]. Environmental samples of air chilling rooms have confirmed the risk of cross-contamination with *Campylobacter* during air cooling of poultry carcasses [53, 74]. These results support the hypothesis that air currents and aerosols are sources of cross contamination during air chilling and highlight the risk of cross-contamination during air and evaporative chilling of poultry.

Slight increases in spoilage bacteria have been reported during immersion [27, 58, 60] or air chilling [58, 60, 61]. The median values of the increase in levels of spoilage bacteria are 0.33

and 0.28 $\log_{10}$ CFU for air and immersion chilling, respectively (Table 2). Thomson *et al.* [63] reported that immersion chilled carcasses retained lower psychrophilic bacteria during chilling and storage than dry chilled carcasses or combination of dry and immersion chilling. They reported a mean difference of 1.3 $\log_{10}$ CFU of psychrophilic bacteria between immersion and dry chilling. Conversely, Knoop *et al.* [75] reported that wet-chilled poultry carcasses spoiled faster than dry chilled carcasses, and this may be attributed to a difference in the dry chilling method. Knoop and coworkers packaged the carcasses before dry chilling, and the surface of the dry chilled birds were crust frozen at the end of the chilling period [75]. This may have retarded the growth of the psychrophilic bacteria. Thomson *et al.* [76] compared wet-chilling with rapid chilling (CO_2) and reported that the superficial freezing on CO_2 chilled carcasses delayed the microbial growth and resulted in slightly longer shelf life than immersion chilled carcasses. Mielnik *et al.* [77] reported no substantial differences in numbers of bacteria, or in spoilage rate between evaporative and air chilled carcasses. Mulder and Bolder [78] reported no difference in shelf life between evaporative, air, or immersion chilled poultry using either 50ºC for 220 s or 57ºC for 165 s scalding regimens. They found that the initial contamination level of hard scalded poultry was higher than low scalded poultry, but this difference disappeared with storage time [78].

Allen *et al.*, [79] evaluated six commercial poultry chilling system, which included one immersion chiller, four spray chillers and one dry chiller. They reported that immersion chilling effectively reduced *Pseudomonas*, coliforms and aerobic bacteria from the carcass neck skin and from the body cavity. The dry chilling method was effective in reducing the bacteria only in the body cavity, while the other three systems had no effect on microbial numbers. When chlorine

was used a water spray, the microbial counts in the body cavity remained virtually unchanged [79].

The contamination of the chicken surface with pathogens:

Bryan and Doyle [80] reported that the mechanism of contamination of *Salmonella* and *Campylobacter* initially involves retention of bacteria in a liquid film on the skin followed by migration to the skin and entrapment in skin ridges and crevices. Thomas and McMeekin [81] reported that the skin surface of carcasses before evisceration and chilling is covered by a liquid film that contains serum proteins, amino acids, and other suspended soluble compounds that originate from the underlying skin tissue or from processing water used to clean or chill the carcass. These authors suggested that the organic materials in the liquid film may explain the low bactericidal effect of chlorine on the carcass. These authors also reported that scalding and defeathering caused the removal of the outer skin layer of broilers and the exposed dermal skin tissue provides a new attachment surface that is irregular, smoother, and less hydrophobic than that of the epidermis [81]. The organic material in the liquid film, the less hydrophobic surface, and the irregular topography of the skin may provide a better explanation about the poor bactericidal effect of chlorine. Thomas and McMeekin [82] using scanning electron microscopy reported that immersion in water caused collagen associated with connective tissue to expand and form a network that may facilitate the attachment or physical entrapment of *Salmonella*. Moreover, these authors suggest that this network may serve as physical protection for bacteria against sanitizers [82].

Lillard [83] showed that water and bacteria move from a surface liquid film to the skin during prolonged water immersion. After 0.25 minutes of immersion, the water uptake in the

surface film accounted for 95.2% of the total uptake. Also, the number of bacteria in the water film accounted for 94.1% of the total bacteria, but after 60 minutes of immersion, the water and the bacteria in the surface accounts for 42.6% and 38.7%, respectively. Therefore, 61.3% of the bacteria were transferred from the surface to the skin by water absorption.

To minimize the transfer of bacteria in chiller water to non-contaminated carcasses, commercial poultry processors typically use antimicrobial treatments. Chlorine is the most widely used antimicrobial treatment in the food industry. It has been used in poultry processing for more than 40 years to reduce spoilage bacteria, control the spread of pathogens, and prevent build-up of microorganisms on working surfaces and equipment [84]. The antimicrobial activity of super-chlorinated processing water against any particular bacteria is affected by the initial microbiological contamination (level), the pH of the solution, the amount of organic material, the concentration of chlorine, and the degree of exposure of the bacteria to the solution. When chlorine is dissolved in water, it hydrolyzes rapidly to the form of hypochlorous acid [$Cl_2 + H_2O = HOCL + CL^-$], which is the species of chlorine with the greatest germicidal properties [85]. Hypochlorous acid is a weak acid and undergoes partial dissociation to produce a hydrogen ion and hypochlorite ion [$HOCL = H^+ + OCl^-$] in a solution with a pH between 6.5 and 8.5. Typically at these pH values, hypochlorous acid and hypochlorite ions are present in some degree [85]. In water with a temperature of 5º C and pH of 8.5, only 15% of the hypochlorous acid is in its undisassociated form, compared with a solution with the same temperature at pH 6.5 where 95% of the hypochlorous acid is in undisassociated form [85].

The complete germicidal effect of chlorine is still unclear, but there is evidence that chlorine reacts irreversibly with the enzymatic system of bacteria resulting in the inability to produce energy. Enzymes that contain sulfhydryl groups may be irreversibly oxidized by

chlorine. The most significant enzyme affected by chlorine is the enzyme triosephosphate dehydrogenase, which is essential for the digestion of glucose [85]. The active form of chlorine, hypochlorous acid, is similar in structure to water, and easily penetrates the cell wall of bacteria because of its low molecular weight and its absence of electrical charge [85]. Hypochlorite ions (OCl-), are poor disinfectants because the ions can not penetrate through the cell wall because of the negative charge [85].

In conventional immersion chillers, the solids contents of the water varies with the chiller design, the rate of production, cleanliness of the carcasses, fat content of carcass, and processing methods [86]. During normal operation, the content of organic material in the chiller increases during the day, reaching equilibrium after 5 to 6 hours of operation between solids lost in overflow water and solids gained from incoming birds [86]. But this will depend on the level of water overflow. Chlorine reacts with the organic material in the chiller water. The amount of chlorine consumed in this reaction represents the chlorine demand of the chiller and is determined by the difference between the amount of chlorine applied and the amount of residual chlorine measured in the water [87]. In general, when the difference is positive, the excess amount of chlorine will be present as free chlorine [87]. Chiller chlorine demand was investigated by Tsai *et al.* [87], and they concluded that poultry chillers require more that 400 ppm of chlorine to saturate the compounds that react and neutralize the microbiocidal activity of chlorine. Considering that actual FSIS regulations allows no more than 50 ppm of total chlorine during poultry processing, free chlorine will be depleted after a very short period of time. The bactericidal effect of chlorine at this level may be limited to the bacteria in the water and those in the vicinity of the fresh water input where the organic material is more dilute. The concentration of organic material in chilling water is also affected by the amount of water overflow. Mead and

Thomas [27] reported that increasing the rate of water usage prolonged the presence of free residual chlorine in the water due to a dilution of the organic material in solution. These authors also addresses the advantage in using a chilling system with more than one tank and the importance of washing the carcasses thoroughly before they reach the chilling system [27]. Both of these operational changes reduce the potential for carcass cross-contamination during immersion chilling.

Yang *et al.* [37] reported that chlorine levels of 50 ppm were effective in reducing *Campylobacter* and *Salmonella* in chiller water, but chlorination did not effectively reduce the bacteria attached on the chicken skin. Mead *et al.* [88] reported that 10 to 20 ppm total chlorine in the processing plant water supply caused little reduction in carcass contamination, but the bacterial load in the chilling water was reduced by approximately 1 log cfu/mL. Lillard [89] reported an incidence of *Salmonella* in post-chill carcasses of 42%, 16%, 0% when 0, 20, and 34 ppm of total chlorine were added to the chiller water. Mead and Thomas [27] reported that concentrations as low as 10 to 15 ppm of total chlorine were effective in reducing fecal and spoilage bacteria in chiller water. Lillard [90] concluded that treatment of chiller water with 34 ppm and 20 ppm of chlorine significantly reduced numbers of bacteria in both water and on carcasses, and significantly extended the shelf life of poultry compared with poultry processed with non-chlorinated water, However, shelf life of products processed with chlorine were similar regardless of the chlorine concentrations [90].

Thomson *et al.* [41] reported that total chlorine levels of 20 and 50 ppm reduced poultry carcass cross-contamination with *Salmonella*. Patterson and McMeekin [91] reported that using 100 and 200 ppm of chlorine did not prevent *Pseudomonas* spoilage of neck skin. These authors attributed their results to the protection that the connective tissue provides to bacteria and to the

rapid inactivation of the chlorine. Bartenfeld *et al.* [92] rinsed poultry carcasses with either a concentrated chlorine solution (500 ppm) or with distilled water (control) and found that chlorine significantly reduce the numbers of *E. coli* and coliforms recovered from broiler carcasses, but no significant reduction in *Salmonella* prevalence was observed (14/38 positive for control; 16/38 positive for chlorine). Review of published information suggest that super-chlorinated water may have a positive effect on reducing carcass cross-contamination during immersion chilling, but chlorine is not effective at killing bacteria present in the skin surface of the carcasses.

Effects of the chilling method on the water uptake:

Poultry carcass moisture retention during immersion chilling may be influenced by the type and number of chill tanks, chilling time, water temperature, extent and type of agitation (air injection or mechanical), method of evisceration, space between meat and skin, degree of exposed flesh, carcass to water ratio, carcass weight, amount of carcass fat, and the addition of electrolytes [15, 30, 93-97]. Immersion chilling, the appearance of the carcasses improves, but excessive water uptake may have negative consequences for consumers and processors because of excessive dripping during distribution and further processing, excessive weepage during thawing, higher transportation cost and reduced quality [6, 7].

Previously reported values of poultry carcass moisture retention after immersion chilling, ranging from 6 to 12%, are summarized in Table 3. During air chilling, carcass weight loss due to evaporation may be as much as 3% or more, compared to evaporative chilling where carcass water absorption is controlled and limited to 2% or less. Mulder *et al.* [19] reported coefficients

of variation of 25 % to 40 % for water uptake in immersion chillers, depending upon the factors listed above.

Poultry carcass moisture retention measured as the difference between pre-washed and post-chill weights or post-chill and post-drip weights, typically underestimate the actual amount of water pick-up. During immersion chilling, considerable amount of fat and body tissue are lost and water is absorbed [19]. In a study conducted by Hale and Stadelman [96], immersion chilled carcasses lost more weight (2%) during cooking than dry air chilled carcasses. These researchers suggested that the difference in the net change of carcass weight was due to body tissues leaching out and being masked by water pick-up. Conversely, Klose *et al.* [97] found that final cooked yield of poultry carcasses, expressed as percentage of original eviscerated weight did not differ appreciably between immersion chilled (ice-water) carcasses and air chilled carcasses. These conflicting results may be explained by differences in chilling equipment and chilling times. The former used commercial equipment and 45 min dwell time, while the latter used an adapted experimental chiller and 30 min dwell time.

Poultry carcass moisture retention is important because the USDA-FSIS issued a rule to limit the amount of water retained by poultry. According to this regulation, poultry carcasses and carcass parts are not permitted to retain water unless it is an unavoidable consequence of processing used to meet food safety requirements. Moreover, processing plants are required to collect data documenting the amount of water absorbed and disclose this information on their labels [1].

In Europe, regulations require processing establishments to comply with specific requirements with respect to water content of frozen whole chickens. The requirements are applicable only to frozen and quick-frozen whole chickens and stipulate that the added water

content should not exceed the technically unavoidable limits. Each chilling method has a limit for the maximum amount of water permissible, and the regulations specify that checks must be carried out using either of two alternative tests - the determination of the total water content (chemical test) or thaw loss (drip test). For the chemical test, the associated water limits are as follows: air chilling 2.0 percent, air-spray chilling 4.5 percent and immersion chilling 7.0 percent. For the drip test, the associated water limits are: air chilling 1.5 percent, air-spray chilling 3.3 percent and immersion chilling 5.1 percent.

Water absorbed during immersion chilling mainly accumulates in the subcutaneous layer and penetration of the meat is limited. Moisture penetration through the skin of poultry is negligible, and the intact skin acts as a barrier against water uptake. Water retained in the outer surface of the carcass skin represents 0.5 to 1.0% (dependent upon the carcass size) of the total water absorbed [10]. At the entrance of the chilling system, the temperature of chicken carcass is about 38º C. The skin lipids are still fluids at this temperature, allowing water to penetrate the skin. As the carcass temperature decreases, the tissue lipids solidify and “seal in” the water absorbed in the prechiller [12]. Thomas and McMeekin [82, 98] suggested that water picked up by breast skin caused capillary-sized channels and spaces to open in the surface layers.

Sanders [99] used a dye tracer and demonstrated that chiller water penetrated the skin mainly in the feather follicles and injured surface (cuts, tears). The muscles did not show any general pattern of penetration even in the areas directly under the feather follicles, and body-cavity openings resulted in the primarily route of dye entry to areas under the skin. When agitation was provided during chilling, the extent of dyed muscle surface and penetration beneath that surface was significantly increased [99]. Klose *et al.* [97] reported that approximatelt half of the weight gained during immersion chilling was lost during subsequent drainage, and most of

the absorbed water was loosely held in pockets between the tissues. These authors also reported that fillets from air chilled carcasses and immersion chilled carcasses had similar moisture content [97]. Bigbee and Dawson [93] reported that more water was picked up by the tissues when longer chilling times were used, but water loss during storage was higher. Water uptake was reported to be 11.7 % with mechanical agitation or 2 % without agitation [97]. These same researchers also reported that the tumbled carcasses lost 3.5 % more weight during cooking. Dickens and Cox [30] reported that the percentage of moisture pickup increased from 5.8% to 13.9% when air was injected (agitation) during water chilling.

During air chilling, poultry carcass weight loss is caused by evaporation and drip. The principal purpose of evaporative chilling is to reduce carcass weight loss during chilling, by intermittent spraying of water onto carcasses to replace moisture lost by evaporation [100]. With evaporative chilling, the surface of carcasses remains wet, and heat is removed with minimal change in carcass weight. Carcass weight loss during evaporative chilling increases with longer chilling time [100]. Research on lamb carcasses has indicated that approximately 60% of the weight loss during air cooling is due to evaporative losses of moisture from the water added during washing, while the remaining 40% is due to evaporative losses of moisture from carcass components [101]. The rate of evaporation is dependent on the velocity of the air passing over the product surface, the difference in the air and the surface temperature, the concentration of water on the surface of the meat and the relative humidity of the cold room [102]. By reducing the difference in water content between the air and the meat surface, the weight loss is minimized [102]. In general, faster cooling rates reduce weight losses, and faster chilling rate is the result of the combination of air temperature and velocity [103, 104].

Effect of chilling method on quality and functionality:

Mielnik *et al.* [77] studied the effects of evaporative and air chilling systems on poultry carcass quality and reported that air chilled carcasses were darker (lower L* values) and more yellow (higher b* values) than evaporative chilled carcasses. These authors suggested that water spraying during evaporative chilling prevented carcass skin from becoming dehydrated, thus ensuring a lighter color. Lyon and Cason [105] compared pre- and post- immersion chilled carcass skin color and found that chilling significantly increased skin lightness (L*=61.6 pre-chill vs 64.6 post-chill). Fleming *et al.* [106] compared the effect of chilling method (air and immersion) on breast fillet color, and reported no significant difference in lightness (L*), redness (a*) and yellowness (b*) values of raw breast fillets harvested form either air or immersion chilled carcasses; however these authors reported that chilling by immersion significantly reduced the concentration of heme pigments in carcass tissue.

Temperature of the breast muscle during rigor development has been demonstrated to affect meat quality [107-111]. Previous research has indicated that elevated temperatures or slower chilling rates accelerate post-mortem glycolysis, and ultimate meat texture and functional properties [112-116].

Dunn *et al.* [113] compared carcass quality after either fast air chilling (–12°C for 50 min) or normal air chilling (80 min at 0°C + 2 h at 4° to 6°C) and reported no significant difference in cooked fillet shear force or cook yield between chilling methods. Perumalla *et al.* [117] reported that chilling method did not affect broiler breast fillet marinade pick-up, cook loss and tenderness. Bauermeister *et al.* [118] reported that fillets from commercial air chilled carcasses deboned as early as 2 h post-mortem had lower shear values and cook loss than immersion chilled carcasses purchased at a local grocery store. In another study, Alvarado *et al.*

[119] reported no significant difference in breast fillet cook loss between air and immersion chilling. The same researchers found that air chilled fillets had significantly higher pH (5.64 vs. 5.56), lower L* value (50.13 vs. 54.73), higher marinade pick-up (15.51% vs. 14.07%) and lower shear value (3.62 vs. 4.14 kg/g) than the immersion chilled fillets. Alvarado *et al.* [119] reported that breast fillets were collected from different commercial operations, and therefore, their results may reflect differences in the biochemical status of the meat (flock variations, differences in plant processing procedures) rather than any chilling effect.

Conclusion:

During poultry processing, chilling is critical because it affects both carcass microbiology and quality. Air, immersion and evaporative chilling systems are the three methods commonly used by commercial poultry processing establishments. It is clear, from many review articles on this subject, that there is a difference in carcass water absorption and appearance, but additional information on chilling and its effect on meat functionality, meat quality, hygienic operation and cross contamination is needed. The objective of the present work was to evaluate, under the same processing conditions and using the same carcass source, the effects of chilling method on bacteria recovery, carcass quality, meat functionality and meat quality.

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TABLE 1.1. Prevalence of *Salmonella* and *Campylobacter* recovered from carcasses before and after chilling.

Chilling Method	Details	Unit	Pre-chill	Post-chill	Referece
Salmonella					
Air		Log CFU/mL	1.2	0.9	Fluckey, 2003
Air		% positive	15/20	15/20	EEC, 1979
Immersion		% positive	15/20	12/20	
Immersion	Parallel flow	% positive	17%	16%	Karolyi *et al.*, 2003
	Counter flow	% positive	17%	11%	
Immersion	Samples before IOBW and after chiller	% positive	18/90 (20%)	17/90 (19%)	Cason *et al.*, 1997
Immersion	Spin Chiller	% positive	17.7 %	21.5 %	McBride *et al.*, 1980
Immersion	Experimental unit, 0 ppm of chlorine	% positive	10/40 (25%)	85%	Thomson *et al.*, 1979
Immersion	Commercial chiller – fecal contaminated	% positive	6/16 (37.5%)	2/16 (12.5%)	Jimenez *et al.*, 2002
	Commercial chiller – non contaminated	% positive	2/20 (10%)	6/20 (30%)	
Immersion	Commercial conditions	% positive	52/100	13/100	Mikolajczyk and Radkowski, 2002
Immersion	Commercial conditions	% positive	4/32 (12.5%)	15/66 (22.7%)	Vadhanasin *et al.*, 2004
Immersion	Controlled experiment	% positive	24/48 (50%)	16/48 (33%)	Smith *et al.*, 2005
Immersion	Controlled experiment	% positive	40/72	11/72	Northcutt *et al.*, 2003
		Log CFU/mL	1.3	0.8	
Immersion	Commercial chiller without chlorine	% positive	5/40 (12.5%)	11/40 (27.5%)	Lillard, 1990
	Commercial chiller without chlorine	% positive	4/40 (10%)	15/40 (37.5%)	
	Commercial chiller without chlorine	% positive	12/84 (14.3%)	31/84 (36.9%)	
Air	0º to 5º C for 75 min	% positive	100%	100%	Abu-ruwaida 1994
			100%	100%	

Immersion	Commercial chiller without chlorine	% positive	70%	60%	Carramiñana, 1997
Immersion	2 stages, countercurrent, 3 ½ *L*/carcass	% positive	9.0%	7.1%	Mulder *et al.*, 1976
	2 stages, countercurrent, 2 ½ *L*/carcass	% positive	14.8%	6.7%	
Immersion	Commercial operations (7 plants)	% positive	20.7%	5.7%	Bilgili *et al.*, 2002
Immersion		% positive	77/160 (48%)	114/158 (72%)	FAO, 2001
		% positive	28/99 (28%)	24/49 (49%)	
		% positive	5/40 (13%)	11/40 (28%)	
		% positive	4/40 (10%)	15/40 (38%)	
		% positive	12/84 (14%)	31/84 (37%)	
		% positive	2/60 (3%)	18/120 (15%)	
Campylobacter					
Air		Log MPN/100mL	2.25	2.1	Fluckey, 2003
Immersion		% positive	90/90 (100%)	89/90 (99%)	Cason *et al.*, 1997
		Log CFU/mL	5.31	3.80	
		Log CFU/mL	5.39	3.91	
Immersion	counter current, 40 -50 ppm	Log CFU/mL	4.75	3.03	Stern and Robach, 2003
Immersion	Commercial operations (7 plants)	Log CFU/mL	1.7	0.8	Bilgili *et al.*, 2002
Immersion	30 minutes, 1º C	Log CFU/mL	2.1	0.7	Dickens *et al.*, 2003
Immersion	Experimental unit, inoculated carcass	% positive	24/48 (50%)	16/48 (33%)	Smith, *et al.*, 2005
Immersion		% positive	71/72	60/72	Northcutt *et al.*, 2003
		Log CFU/mL	2.9	1.6	
Immersion	Two section counter current		40/40	36/38	Berndtson *et al.*,1996
Air		Log CFU/g (% positive)	3.23 (100%)	2.54 (100%)	Rosenquist *et al.*, 2006
			2.40 (100%)	1.43 (73.3%)	

Immersion			3.83 (100%)	2.59 (100%)	
			3.93 (100%)	3.24 (100%)	
Immersion	Commercial operation, no chlorine	Log CFU/g (% positive)	2.62 (73.3%)	1.38 (80%)	Wempe *et al.*,1983
	Commercial operation, no chlorine		2.92 (66.7%)	1.74 (93.3%)	
	Commercial operation, no chlorine		3.32 (66.7%)	1.33 (60%)	
	Commercial operation, 12 ppm chlorine		2.50 (100%)	1.76 (86.7%)	
Air	Dry chilling		3%	3%	Lindblad *et al.*, 2006
	Dry chilling		10%	9%	
	Dry chilling		23%	13%	
Evaporative	Spry chilling		10%	9%	
Immersion	Immersion		33%	43%	
	Immersion + air chilling		22%	22%	
Air	Air for 120 minutes to 4º C	% positive	36%	34%	Houf *et al.*, 2002
	Air for 22 minutes to 18º C	% positive	80%	90%	
Immersion	Immersion for 30 minutes to 11º C	% positive	50%	48%	
Air	Air for 80 minutes to 15º C	% positive	14%	0%	
	Air for 60 minutes to 10º C	% positive	78%	66%	
	Air for 75 minutes to 12.5º C	% positive	46%	38%	
	Air for 60 minutes to 4º C	% positive	98%	86%	
	Air for 62 minutes to 13º C	% positive	26%	8%	
Immersion	pH 7.2; 25 ppm of chlorine		4.25 (80%)	4.12 (73.3%)	Bashor *et al.*, 2004
	pH 7.0; 35 ppm of chlorine		4.10 (80%)	3.85 (70%)	
	pH 11.2		3.58 (80%)	3.42 (60%)	
	pH 6.8; 35 ppm of chlorine		3.38 (63.3%)	3.31 (63.3%)	
Immersion	Commercial operation	Log CFU/mL	1.14	0.64	Kemp *et al.*, 2001

		% positive	49.1	57.6	
Air	0º C for 55 minutes.	Log CFU/g (pericloacal skin)	2.24	3.73	Oosterom *et al.* 1983
	0º C for 55 minutes.		2.50	< 0.30	
	0º C for 55 minutes.		2.62	< 0.30	
Immersion	Counter-flow spin chiller	Log CFU/g (pericloacal skin)	2.58	0.98	
	Counter-flow spin chiller		2.44	1.24	
	Counter-flow spin chiller		2.60	1.83	
Immersion			5/30	6/30	Reiter *et al.*, 2005
Air	Pre-chill (20 minutes)		31/43	29/43	Alter *et al.*, 2005
	After complete chill (24h)		31/43	11/43	
Immersion	Counter flow	% positive	6.25%	9.38%	Karolyi *et al.*, 2003
	Parallel flow	% positive	6.25%	12.5%%	
Air	0º to 5º C for 75 min.	Log CFU/g (neck skin)	5.5	5.3	Abu-Ruwaida 1994

TABLE 1.2. Numbers of Total Aerobic Bacteria (Aerobes), Coliforms, *Escherichia coli*, *Enterobacteriaceae*, Psychrotrophic spoilage bacteria, and Pseudomonas recovered from carcasses before and after chilling.

Chilling Method	Details	Unit	Pre-chill	Post-chill	Referece
Total Aerobic Bacteria					
Air	0º to 5º C for 75 min.	Log CFU/g	6.0	6.0	Abu-Ruwaida 1994
	0º to 5º C for 75 min.	Log CFU/g	6.3	6.1	
Immersion	Commercial operations (7 plants)	Log CFU/mL	4.2	3.2	Bilgili *et al.*, 2002
Immersion	Samples before IOBW and after chiller	Log CFU/mL	7.13	5.27	Cason *et al.*, 1997
Air	Samples before IOBW and after chiller	Log CFU/mL	3.81	3.23	Fluckey *et al.*, 2003
Immersion	Two sections for 25 minutes	Log CFU/cm^2	3.1	2.5	Thomson *et al.*, 1975
Air	2-3 m/s; 2º C for 55 minutes	Log CFU/g	4.77	4.78	Graw *et al.*, 1997
	5 8 m/s; 3º C for 75 minutes	Log CFU/g	5.62	5.51	
Evaporative	2-3 m/s; 2º C for 55 minutes	Log CFU/g	4.73	4.29	
	5 8 m/s; 3º C for 60 minutes, 1.41 L/b	Log CFU/g	5.73	5.22	
air	2º C to 8º C, for 45 – 60 minutes	Log CFU/g	4.87	5.12	Whyte *et al.*, 2004
	2º C to 8º C, for 45 – 60 minutes	Log CFU/g	4.44	4.47	
Immersion		Log CFU/cm^2	3.17	2.57	Cox *et al.*, 1975
Immersion	Parallel flow	Log CFU/cm^2	4.06	6.13	Petrak *et al.*, 1999
	Parallel flow	Log CFU/cm^2	4.24	6.49	
	Counter flow	Log CFU/cm^2	3.72	3.91	
	Counter flow	Log CFU/cm^2	4.02	4.12	
Immersion	20 – 45 minutes	Log CFU/cm^2	4.70	3.74	Blank and Powell, 1995
Immersion	3 unit counter flow, 25 to 60 ppm chlorine	Log CFU/g	4.6	4.4	Mead *et al.*, 1993

Air	2 to 6º C for 4 hours	Log CFU/g	4.8	5.1	
Immersion	2 unit counter flow, 30 to 70 ppm chlorine	Log CFU/g	4.4	3.6	
Air	4 to 11º C for 1 hour	Log CFU/g	4.4	4.4	
Air	6 to 15º C for 1 hour	Log CFU/g	4.6	4.7	
immersion	2 stages, countercurrent, 3 ½ L/carcass	Log CFU/g	4.28	4.11	Mulder *et al.*, 1976
	2 stages, countercurrent, 2 ½ L/carcass	Log CFU/g	4.10	4.02	
Immersion	1.7 L/carcass; and 20 to 50 ppm of chlorine	Log CFU/cm^2	4.08	3.91	Mead and Thomas, 1973
	1.7 L/carcass; no Chlorine	Log CFU/cm^2	4.26	3.23	
Immersion	Commercial chiller without chlorine	Log CFU/mL	6.69	5.78	Lillard, 1990
	Commercial chiller without chlorine	Log CFU/m	6.67	5.94	
	Commercial chiller without chlorine	Log CFU/mL	6.46	5.87	
Immersion	1 unit, 45 min, 3.5 L/carcass	Log CFU/mL	4.96	4.80	EEC, 1978
	2 units, 37 min, 3.73 L/carcass	Log CFU/mL	5.92	5.77	
	2 units, 67 min, 3. 3 L/carcass	Log CFU/mL	6.62	6.47	
	2 units, 30 min, 3. 1 L/carcass	Log CFU/mL	5.05	4.93	
Air	30 min, 0º C	Log CFU/mL	4.96	4.83	
	2 hours, 0º C	Log CFU/mL	5.92	5.90	
	5 hours, 2º C	Log CFU/mL	6.36	6.50	
Air	-6º C to 2º C; 100 minutes	Log CFU/g	5.00	4.80	Gonzalez-Miret *et al.* 2005
Air	Walk-in air chiller	Log CFU/mL	2.92	2.65	Schneider *et al.*, 2002
Coliforms					
Air	0º to 5º C for 75 min.	Log CFU/g	5.1	4.3	Abu-ruwaida 1994
	0º to 5º C for 75 min.	Log CFU/g	5.2	5.0	

Air		Log CFU/mL	3.27	2.59*	Fluckey *et al.*, 2003
Immersion	20 – 45 minutes	Log CFU/cm^2	3.99	3.03	Blank and powell, 1995
Immersion	1.7 L/carcass; and 20 to 50 ppm of chlorine	Log CFU/cm^2	3.26	2.99	Mead and Thomas, 1973
	1.7 L/carcass; no Chlorine	Log CFU/cm^2	2.94	2	
Immersion	3 unit counter flow, 25 to 60 ppm chlorine	Log CFU/g	3.4	2.8*	Mead *et al.*, 1993
Air	2 to 6º C for 4 hours	Log CFU/g	3.6	3.7	
Immersion	2 unit counter flow, 30 to 70 ppm chlorine	Log CFU/g	2.3	< 2.0	
Air	4 to 11º C for 1 hour	Log CFU/g	3.1	3.0	
Air	6 to 15º C for 1 hour	Log CFU/g	3.1	3.0	
Immersion		Log CFU/mL	6.5	5.7	Cason *et al.*, 2004
			6.7	5.8	
Immersion	1 unit, 45 min, 3.5 L/carcass	Log CFU/mL	3.92	3.41	EEC, 1978
	2 units, 37 min, 3.73 L/carcass	Log CFU/mL	3.89	3.80	
	2 units, 67 min, 3. 3 L/carcass	Log CFU/mL	3.99	3.71	
	2 units, 30 min, 3. 1 L/carcass	Log CFU/mL	4.55	3.90	
Air	30 min, 0º C	Log CFU/mL	3.92	3.77	
	2 hours, 0º C	Log CFU/mL	3.89	3.79	
	5 hours, 2º C	Log CFU/mL	3.95	3.88	
Immersion	Pilot scale, 20 ppm	Log CFU/mL	3.9	2.6	Northcutt *et al.*, 2003
Air	Walk-in air chiller	Log CFU/mL	1.22	1.05	Schneider *et al.*, 2002
E. coli					
Air	0º to 5º C for 75 min.	Log CFU/g	4.8	4.4	Abu-Ruwaida 1994
	0º to 5º C for 75 min.	Log CFU/g	4.2	4.1	

Immersion	Commercial operations (7 plants)	Log CFU/mL	2.4	1.2	Bilgili *et al.*, 2002
Air		Log CFU/mL	3.08	2.20*	Fluckey, 2003
air	2º C to 8º C, for 45 – 60 minutes	Log CFU/g	3.26	3.35	Whyte *et al.*, 2004
	2º C to 8º C, for 45 – 60 minutes	Log CFU/g	2.95	3.11	
Immersion		Log CFU/mL	6.3	5.4	Cason *et al.*, 2004
			6.4	5.5	
Immersion	Pilot scale, 20 ppm	Log CFU/mL	3.2	1.8	Northcutt *et al.*, 2003
Air	Walk-in air chiller	Log CFU/mL	1.37	1.21	Schneider *et al.*, 2002
Enterobacteriaceae					
Air	2-3 m/s; 2º C for 55 minutes	Log CFU/g	3.20	3.13	Graw *et al.*, 1997
	5 8 m/s; 3º C for 75 minutes	Log CFU/g	3.32	3.38	
Evaporative	2-3 m/s; 2º C for 55 minutes	Log CFU/g	3.56	3.10	
	5 8 m/s; 3º C for 60 minutes, 1.41 L/b	Log CFU/g	3.98	3.42	
air	2º C to 8º C, for 45 – 60 minutes	Log CFU/g	3.37	3.79*	Whyte *et al.*, 2004
	2º C to 8º C, for 45 – 60 minutes	Log CFU/g	3.17	3.37	
Air	-6º C to 2º C; 100 minutes	Log CFU/g	3.54	3.40	Gonzalez-Miret *et al.* 2005
Immersion		Log CFU/cm^2	2.27	1.48*	Cox *et al.*, 1975
Immersion	2 stages, countercurrent, 2 ½ L/carcass	Log CFU/g	3.39	2.80	Mulder *et al.*, 1976
	2 stages, countercurrent, 1 ½ L/carcass	Log CFU/g	2.70	3.10	
Immersion	Two sections for 25 minutes	Log CFU/cm^2	1.9	1.3*	Thomson *et al.*, 1975
Immersion		Log CFU/mL	5.9	5.6	Cason *et al.*, 2004
			6.3	5.6	
Air	0º to 5º C for 75 min.	Log CFU/g	5.2	5.3	Abu-ruwaida 1994
	0º to 5º C for 75 min.	Log CFU/g	5.2	5.0	

Immersion	Commercial chiller without chlorine	Log CFU/carc	6.01	4.97*	Lillard, 1990
	Commercial chiller without chlorine	Log CFU/carc	6.09	4.97*	
	Commercial chiller without chlorine	Log CFU/carc	5.50	4.89*	
Air	0º C for 55 minutes.	Log CFU/g	3.86	4.89	Oosterom *et al.* 1983
	0º C for 55 minutes	Log CFU/g	3.60	5.26	
	0º C for 55 minutes	Log CFU/g	3.87	4.50	
Immersion	Counter-flow spin chiller	Log CFU/g	5.73	4.25	
	Counter-flow spin chiller	Log CFU/g	3.60	3.17	
	Counter-flow spin chiller	Log CFU/g	4.86	4.04	
Psychrotrophic bacteria					
Air	2º C to 8º C, for 45 – 60 minutes	Log CFU/g	4.79	5.12*	Whyte *et al.*, 2004
	2º C to 8º C, for 45 – 60 minutes	Log CFU/g	4.38	4.46	
Immersion	1.7 L/carcass; and 20 to 50 ppm of chlorine	Log CFU/cm^2	4.56	3.11	Mead and Thomas, 1973
	1.7 L/carcass; no Chlorine	Log CFU/cm^2	4.62	4.90	
Immersion	1 unit, 45 min, 3.5 L/carcass	Log CFU/mL	4.43	4.64	EEC, 1978
	2 units, 37 min, 3.73 L/carcass	Log CFU/mL	3.36	3.71	
	2 units, 67 min, 3. 3 L/carcass	Log CFU/mL	4.77	5.05	
	2 units, 30 min, 3. 1 L/carcass	Log CFU/mL	2.70	3.93	
Air	30 min, 0º C	Log CFU/mL	4.43	4.24	
	2 hours, 0º C	Log CFU/mL	3.36	4.21	
	5 hours, 2º C	Log CFU/mL	4.76	5.00	
Pseudomonas					
Immersion	3 unit counter flow, 25 to 60 ppm	Log CFU/g	2.7	3.3	Mead *et al.*, 1993

	chlorine				
Air	2 to 6º C for 4 hours	Log CFU/g	2.7	3.9	
Immersion	2 unit counter flow, 30 to 70 ppm chlorine	Log CFU/g	2.2	< 2.0	
Air	4 to 11º C for 1 hour	Log CFU/g	< 2.1	2.6	
Air	6 to 15º C for 1 hour	Log CFU/g	<2.2	3.2	
Air	-6º C to 2º C; 100 minutes	Log CFU/g	3.34	3.20	Gonzalez-Miret *et al.* 2005

TABLE 1.3. Summary of research on broiler carcass yield after chilling.

Method of chilling	Details	Weight change	Reference
Immersion Chilling	45 min in mechanical chiller	7.37 %	Hale *et al.*, 1973
	30 min, ice slush, still	2.0 %	Klose *et al.*, 1960
	30 min, ice slush, tumbling	11.7 %	Klose *et al.*, 1960
	1 hour, ice slush, still	2.8% - 3%	Fromm and Monroe, 1958
	3 hour, ice slush, still	4.3% - 4%	Fromm and Monroe, 1958
	5 hour, ice slush, still	5% - 4.8%	Fromm and Monroe, 1958
	24 hour, ice slush, still	6% - 6.6%	Fromm and Monroe, 1958
	20 min, ice slush, high agitation	12.6%	Sanders, 1969
	20 min, ice slush, mod agitation	12.1%	Sanders, 1969
	20 min, ice slush, no agitation	3.4%	Sanders, 1969
	35 min, 2 sections, slush ice	8.3%	Thomson *et al.*, 1984
	30 min, 4 rpm, 50:50 water:ice	11.7%	Young and Smith, 2004
	25 min, two section chiller	7.4%	Thomson *et al.*, 1975
	Immersion + 45 min air chilling	5.5%	Thomson *et al.*, 1975
	30 min, two section chiller	7.3%	Mulder *et al.*, 1976
	2 hours slush ice, still	4.75%	Bigbee and Dawson, 1963
	4 hours slush ice, still	5.19%	Bigbee and Dawson, 1963
	24 hours slush ice, still	8.31%	Bigbee and Dawson, 1963
Air Chilling	30 min. -35º F blast freezer, packaged	0 %	Hale *et al.*, 1973
	Air Tº 1º C; vel 44 m/min; 2 hours PM[1]	-1.9 %	Sarovsky and Sams, 1999
	Air Tº 1º C; vel 44 m/min; 4 hours PM	- 2.3 %	Sarovsky and Sams, 1999

	Air Tº 1º C; vel 44 m/min; 8 hours PM	- 2.5 %	Sarovsky and Sams, 1999
	2 stages air chilling, final Tº < 4º C	- 1.2%	Veerkamp, 1991
	1 stage; Washing + Chilling	- 1.0%	Veerkamp, 1991
	1 stage; Chilling	- 1.7%	Veerkamp, 1991
	23 h. 37º F in plastic bag	- 0.7%	Klose *et al.*, 1960
	60 min., 2 sprayings of 0.16 L/carcass	- 1.6%	Veerkamp, 1978
	50 min, 0.5 m/s.	- 2.0%	Mielnik *et al.* 1999
	24 h; 2.2 m^3/min, air Tº 2º C.	0.01%	Young and Smith, 2004
	45 minutes, - 7º C. 3.5 m/s	- 1.2%	Thomson *et al.*, 1975
Evaporative Chilling	Initial Tº 38.5º C, final Tº 11.80º C	0.8% to 1.40%	Ristic, 1997
	1 stage 1 x spray; chilling	- 0.8 %	Veerkamp, 1991
	3 stage 2 x spray; Washing + Chilling	- 0.3 %	Veerkamp, 1991
	Chilling	0	Veerkamp, 1991
	Washing + Chilling	1.0%	Veerkamp, 1991
	Chilling	1.0%	Veerkamp, 1991
	60 minutes, 2.5 m/s, 75-80% RH	- 0.6% to -0.8%	Veerkamp, 1978
	50 min, 0.5 m/s, 21.5 L/m	- 0.2%	Mielnik *et al.* 1999

[1] PM = Post mortem

CHAPTER 2

EFFECT OF IMMERSION OR DRY AIR CHILLING ON BACTERIA RECOVERY FROM BROILER CARCASSES[1]

[1] R. Huezo, J. K. Northcutt, D. P. Smith, D. L. Fletcher, and K. D. Ingram. Submitted to J Food Prot.

ABSTRACT

A study was conducted to investigate the effect of chilling method (air or immersion) on numbers and prevalence of *Escherichia coli*, coliforms, *Campylobacter*, and *Salmonella* recovered from broiler carcasses. During each of 4 replications, 60 broilers were inoculated orally and intra-cloacally with 1 mL of a suspension containing approximately 10^8 cells/mL of *Campylobacter*. After one day, broilers were inoculated with 1 mL of a suspension containing approximately 10^8 cells/mL of *Salmonella*. Broilers were processed and carcasses were cooled by dry air (3.5 m/s, -1.1^o C, 150 min) or immersion chilling in ice water (0.6^o C, 50 min). Numbers of *E. coli*, coliforms, *Campylobacter*, and *Salmonella* recovered from pre-chill carcasses averaged 3.5, 3.7, 3.4, and 1.4 Log cfu/mL of rinse, respectively. Overall, both chilling methods significantly reduced bacteria levels on the carcasses, and no difference in numbers of bacteria was observed between the two chilling methods ($P < 0.05$). Both chilling methods reduced *E. coli* and coliforms levels by 0.9 to 1.0 log units. Chilling reduced *Campylobacter* levels by 1.4 log (air) and 1.0 log (immersion), while *Salmonella* reductions were 1.0 log and 0.6 log units for air and immersion chilling, respectively. Chilling method had no effect on the prevalence of *Campylobacter* and *Salmonella* recovered form carcasses. These results demonstrate that air and immersion chilled carcasses, without any chemical intervention, are microbiologically comparable, and a 90% reduction in numbers of *E. coli*, coliforms, and *Campylobacter* can be obtained by chilling.

INTRODUCTION

Increased consumption of poultry products has resulted in improvements in processing technologies, such as carcass chilling systems. Chilling systems typically use water, air, solid carbon dioxide or liquid nitrogen as coolants [1, 2]. Before 1978, immersion systems using water as a coolant were the most widely used chilling method because of efficiency and low cost. However, these systems were criticized because submersion in a common bath was thought to promote cross-contamination. In the late 1970's, a ban on "spin chilling" or auger chilling was implemented in the European Union (EU) because of fear of cross-contamination from water absorption during immersion chilling. This ban resulted in an extensive amount of research on immersion chilling and guidelines for chilling (overflow, countercurrent, chlorine, and carcass to water ratio). Research also focused on developing a suitable alternative for immersion chilling of poultry carcasses that would: 1) overcome the objections of the EU ban; and, 2) satisfy the industry requirements for continuous product flow, efficient energy and water utilization with reasonable installation and operation cost [3]. Alternatives to the classical "spin-chiller" are dry air or evaporative spray chilling, cryogenic chilling, or controlled continuous immersion chilling systems [3].

Air, immersion, and evaporative chilling systems are the three most common methods of cooling poultry used commercially [4]. Several review articles on poultry chilling have been published [1, 2, 5-7]. The main differences reported between the systems are water absorption levels and appearance of the end product. Systems may also

differ in hygienic operation and cross contamination although, scientific documentation of differences is limited.

Previous research has reported that immersion chilling system may reduce levels of *E. coli* and coliforms recovered from carcasses by 1.1 and 0.6 log units, respectively, on average [8-13]. In most of the studies involving air chilling, no significant reductions in *E. coli* or coliforms numbers on carcasses were reported [10, 13-15]. For *Campylobacter*, lower numbers were found on carcasses after either immersion or air chilling, and average reductions of 1.2 and 0.8 log units, respectively, were found [8, 12, 16-21]. Although levels were reduced after chilling, the overall prevalence of *Campylobacter* positive carcasses after chilling was not affected by the method (air or immersion) of chilling [12, 16, 17, 19, 21-26].

Studies have been conducted to evaluate the effect of chilling on numbers and prevalence of *Salmonella*. Both immersion and air chilling have been found to have a minimal effect on the prevalence of *Salmonella* on poultry carcasses [10, 14, 15]. Other researchers have suggested that the washing effect during immersion chilling physically removes bacteria cells to the point to reducing recovery, but this effect is likely offset by carcass cross contamination [21, 25-27]. Air chilling uses little (evaporative spray) or no water. Cross-contamination can occur via aerosols, but not to the same magnitude as immersion chilling [22, 23, 28-30]. Several authors have postulated that surface drying during air chilling reduces water activity, retards bacterial growth and causes enough injury to pathogenic bacteria to reduce recovery [3, 18, 31-33].

In many of the publications that compare numbers of bacteria on chilled poultry carcasses, the effects of the chilling method are obscured by the initial (pre-chill) carcass

bacterial load, chilling operation parameters, the use of antimicrobials, or differences in microbiological sampling techniques. Therefore, it has been difficult to make a true comparison among chilling methods with so many variables. The objective of this study is to determine the effect of chilling method (air or immersion) on *Escherichia coli*, coliforms, *Campylobacter*, and *Salmonella* numbers and prevalence recovered from broiler carcasses.

MATERIALS AND METHODS

Source of birds and inoculation:

For each of four experiments, 60 market age (42 d) broilers of mixed gender were obtained from the live bird holding area of a commercial processing plant. The birds were cooped, transported (about 15 min) to the Russell Research Center animal research facility, and placed on pine shavings in a 5 × 8 m floor pen in a controlled-environment house. Birds were fed nonmedicated, corn-soybean meal-based grower diet (3,200 kcal of ME/kg, 21% CP) for no more than three days, until processing. On the same day they were transferred to the research facility, birds were challenged orally and intra-cloacally with 1 mL of a suspension containing approximately 10^8 cells of *Campylobacter*. Twenty four-hours later, the same birds were given 1 mL of a suspension containing 10^8 cells of *Salmonella* administered both orally and intra-cloacally. Feed was removed at least 4 h prior to inoculation and replaced 4 h following inoculation. Broilers were processed at 44 to 45 d of age. The night before processing, feed but not water was removed for 8 to 10 h before cooping such that the total feed withdrawal time was 10 to 12 h, while water

withdrawal was 2 to 4 h. On the processing day, cooped broilers were transported to the pilot processing plant where they were slaughtered.

Salmonella and Campylobacter cultures and inoculation:

The inoculum cultures were prepared according to the procedure described by Bailey *et al.* [34]. For *Salmonella*, three strains of nalidixic acid–resistant *Salmonella* (*Salmonella typhimurium, Salmonella* Montevideo, and *Salmonella* Enteritidis) were used to inoculate chickens. For preparation of the inoculum, the cultures were streaked onto brilliant green sulfa agar (BGS) (Difco Laboratories, Detroit, MI) plates containing 200 ppm of nalidixic acid (Sigma Chemical Co., St. Louis, MO). Plates were incubated overnight at 37^{o} C. A bacterial suspension was prepared in physiological saline solution, and the optical density (Spectronic 20D+, Thermo Electron Corporation, Waltham, MA) was measured to determine the concentration of the inoculum. *Campylobacter jejuni* cultures were streaked on Campy-Cefex agar [35] and incubated at 42°C for 24 h under microaerophilic conditions (5% O_2, 10% CO_2 and balance N_2) in a BBL™ GasPak® (Becton, Dickson and Company, Sparks, MD) Jar with an activated BBL™ CampyPak® for 24 h and the bacterial suspension was prepared as described before. Unless stated otherwise, these same plating procedures were used for recovery of *Salmonella* and *Campylobacter* from the carcass rinses.

Processing:

For each of the 4 replications, fifty broilers birds were stunned using a commercial stunner (Simmons model SF-7001, Simmons Engineering Co., Dallas, GA)

that was set to deliver 16 V, pulsed DC at approximately 500 Hz for 18 s, followed by 16 V, 60 Hz AC for 9 s. Stunned birds were manually killed by cutting both the carotid artery and jugular vein on one side of the neck (unilateral cut). Birds were allowed to bleed for 120 s, scalded (Cantrell Model SS300CF, Cantrell Machine Co., Inc., Gainesville, GA) at 49.5^{o} F for 120 s, and defeathered (Cantrell Model CPF-60, Cantrell Machine Co., Inc., Gainesville, GA) for 30 s using an in-line picker. After picking, heads and feet were removed manually, and the carcasses were manually eviscerated and washed. Sixteen carcasses were randomly selected and identified by wing tags.

Chilling treatments and microbiological sampling

For the microbiological analyses, the same carcass was sampled by the whole carcass rinse technique (WCR) before and after chilling. Pre and post-chill carcasses were subjected to a low-volume WCR procedure [36]. Carcasses were placed in a bag with 100 mL of 0.1% of peptone solution and placed in an automated carcass shaking machine for 1 min. After shaking, carcasses were removed aseptically and the rinse was sampled for bacteria recovery. For the pre-chill carcasses, rinses in sterile cups were stored on ice for less than 45 min before microbiological analyses. After pre-chill WCR collection, carcasses were randomly assigned to either the immersion or air chilling treatment.

Twenty-four additional carcasses were added to the immersion chiller to obtain commercial chiller volumes (L/kg), and 10 carcasses were added to the air chiller. Immersion chilled carcasses were submersed in 133 L of a mixture of ice and potable water (approximately 0.6^{o} C) in a prototype tumble chiller. The paddles in the tumble

chiller were operated at approximately 2 rpm for the duration of the 50 min chill. Air chilled carcasses were cooled for 150 min with air temperature less than 0º C. The air in the chill room was distributed directly into the abdominal cavity of each carcass by means of flexible channels that were modified to provide a continuous flow of cold air (3.5 m /s) to each carcass.

For both treatments, the internal temperature of the breast of designated carcasses was continuously monitored with a Cox® recorder (Cox® Temperature record system, COX Technologies Company, Belmont, NC). After immersion chilling, carcasses were hung in shackles and allowed to drip for 5 min before the post chill WCR was collected. Air chilled carcasses were subjected to a WCR immediately after the 150 min time period.

Skin samples:

During the last two replications, a sub-set of four carcasses from each treatment was randomly selected after the post-chill WCR. Approximately 20 g of breast skin was aseptically removed from each carcass, placed into a sterile sampling bag (Whirl-Pak® Sampling Bags, NASCO Fort Atkinson, WI), and stored on ice for less than 2 h before analysis.

Microbiological analyses:

Serial dilutions of the rinse diluent were made in 1% peptone. *E. coli* and coliforms were enumerated by transferring 1 mL from serial dilutions onto 3M Petrifilm *E. coli*/coliform count plates (3M Health Care, St. Paul, MN) and incubated at 35°C for

24 h. Blue colonies with entrapped gas were counted as *E. coli*, and all blue and red colonies with entrapped gas were counted as coliforms.

For *Campylobacter* enumeration, 0.1 mL from a series of 1:10 dilutions were plated onto Campy-Cefex agar and plates were incubated at 42°C for 48 to 72 h in a microaerophilic atmosphere. Presumptive colonies of *Campylobacter* spp. were examined microscopically for typical motility and cell morphology, and colonies were confirmed using a latex agglutination test kit (Panbio, Inc., Columbia, Md). For *Salmonella*, 0.1 mL of the rinsate was directly plated onto brilliant green sulfa agar (BGS) plates containing 200 ppm nalidixic acid and plates were incubated for 24 h at 35°C.

For *Salmonella* pre-enrichments (only during the last two replications), 5 mL of 10X concentrated buffered peptone water was added to 45 mL of rinsate. After incubation for 24 h at 37^{o} C, enriched samples were plated onto BGS plates containing 200 ppm nalidixic acid. Plates were incubated for 24 h at 37^{o} C and then inspected for typical *Salmonella* colonies.

Microbiological analyses of the skin sample were performed using the procedure described by Hinton and Ingram [37]. This method involves stomaching skin with peptone water (1:2 wt/vol) for 120 sec on high speed. Aliquots of the peptone-water were removed after stomaching for microbial analyses. *E. coli*, coliforms and *Campylobacter* were cultured using the procedures described above.

Statistical analysis:

Bacterial numbers per mL of rinsate or per gram of skin were converted to Log units for statistical analysis. Differences between chilling method were tested using the

ANOVA procedure of the general linear model of SAS software with replication and chilling method as the main effects of the model [38]. Main effects and their interactions were tested for statistical significance ($P < 0.05$) using the residual error. When the interaction between chilling method and replication was found to be significant, it was used as the error term for the main effect. A paired t-test from the readings of the same carcass was used to test the significance of the bacterial reductions pre and post chilling. *Salmonella* and *Campylobacter* prevalence were analyzed using the chi-squared test for independence.

RESULTS AND DISCUSSION

The mean logarithmic microbial numbers for *E. coli*, coliforms, *Campylobacter* and *Salmonella* recovered from broiler carcass rinses before and after air or immersion chilling are shown in Table 1. Before chilling, numbers recovered from carcasses averaged 3.5, 3.7, 3.4, and 1.4 Log cfu/mL of rinse for *E. coli*, coliforms, *Campylobacter*, and *Salmonella* respectively. No difference was observed in the initial bacteria load (pre-chill) for carcasses, indicating comparable bacterial numbers prior to treatment ($P > 0.05$). Also, no significant difference was observed in *E. coli*, coliforms, and *Salmonella* numbers recovered from air or immersion chilled carcasses. However, a slight but significant difference was found for *Campylobacter* numbers with lower counts observed on air chilled carcasses compared to immersion chilled carcasses ($P < 0.05$).

Overall, both chilling methods reduced bacteria numbers recovered from carcasses, and the level of reduction was similar for both air and immersion chilled

carcasses ($P < 0.05$). Sampling the same carcass before and after chilling provided a more sensitive comparison than simply analyzing the post chill bacteria levels of the two treatments. This comparison eliminated pre-existing differences among individual carcasses allowing a better comparison of chilling methods. Air and immersion chilling reduced *E. coli* and coliforms numbers recovered from carcasses by 0.9 to 1.0 log units. A slightly higher reduction in *Campylobacter* was observed during air chilling (1.4 log) compared with immersion chilling (1.0 log) but this difference was not statistically significant. For *Salmonella*, reductions of 1.0 log and 0.6 log units were observed during air and immersion chilling respectively, and the difference between chilling methods was not statistically significant (Table 1).

The data from immersion chilling agrees with the previously cited publications [8-13, 16-21], but the significant bacteria reduction during air chilling was unexpected. Most of the available publications on air chilling, report bacteria counts as cells per g of macerated skin (breast or neck skin) or per cm^2 of area, while most immersion chilling publications use a whole carcass rinse technique (cfu/mL rinse). Allen *et al.* [31] conducted an air chilling experiment in a controlled environment and reported that dry chilling did not affect the bacteria numbers recovered from breast skin, but it effectively reduced the numbers of bacteria recovered from the body cavity. They attributed this finding to a more severe drying of the body cavity; however, it could also be related to surface differences between the skin and the cavity. Thomas and McMeekin [39], reported that the skin surface of the carcass before evisceration and chilling is covered by a liquid film. This liquid film consists of serum proteins, amino acids, and other suspended soluble compounds that originate from the underlying skin tissues or from

processing water. It has been suggested that bacteria within the liquid film may be protected from cleaning and disinfection. Smith *et al.* [40] evaluated the microbiological characteristics of poultry carcasses contaminated internally (carcass cavity) or externally (breast skin) with fecal material (1 g of cecal content) and washed in a commercial inside-outside bird washer. They demonstrated that washed carcasses with internal contamination had lower numbers of *E. coli* (4.2 vs. 4.9 log cfu/mL), coliforms (4.5 vs. 5.0 log cfu/mL), and *Campylobacter* (2.6 vs. 3.6 log cfu/mL) than washed carcasses with external contamination. Lillard [41] using consecutives rinses of the skin and carcass cavity suggested that bacteria present on the skin or inside the carcass cavity detach in a similar manner. More information is required to evaluate the susceptibility of bacteria in the skin surface or inside the carcass cavity to processing procedures.

The research by Allen and coworkers [31] may also explain the difference between the air chilling results of the present experiment. The whole carcass rinse technique is more likely to detect bacteria reductions for the total carcass, while the skin dissection technique is effective for changes occurring on the sampled surface only. Gill and Badoni [42] reported that evaporative chilling reduced bacterial numbers by 0.42 and 0.11 log cfu/cm^2 for *E. coli* and coliforms, respectively, when they used a skin excision technique, and reductions of 0.73 and 0.32 log cfu/mL for *E. coli* and coliforms, respectively, when they used WCR. Fluckey *et al.* [15] reported that air chilling significantly reduces the numbers of coliforms and *E. coli* by 0.7 and 0.8 log units, respectively, using the WCR sampling technique.

Chilling by air or immersion had no effect on the prevalence of *Campylobacter* positive carcasses (100% recovered pre- and post-chill). For direct enumeration of

Salmonella, 31 carcasses were positive out of 64 pre-chill carcasses tested. No significant difference was found in the pre-chill (18/32 for AC vs 13/32 for IC) and post-chill (8/32 for AC vs 7/32 for IC) prevalence of *Salmonella* for air and immersion chilling. A significant reduction in prevalence from 56% (18/32) pre-chill to 25% (8/32) post-chill was found after air chilling ($P < 0.05$). The prevalence of *Salmonella* positive carcasses for pre- and post-immersion chilling was 40% (13/32) and 22% (7/32) respectively. A similar trend in *Salmonella* prevalence was reported by Northcutt *et al.* [12], 56% (40/72) of carcasses were positive for *Salmonella* before chilling, but only 15% (11/72) after immersion chilling. The use of a pre-enrichment step in the present study increased *Salmonella* recovery to 100% before and after chilling.

Pre-enrichment of microbial samples allows recovery of bacteria that are injured. Bacteria are injured by physical stressors such as temperature or dryness, resulting in a progressive loss of culturability on selective media, although the bacterial cells remain metabolically active [43, 44]. The cell envelope is a common site of injury by chilling, freezing or heating. A variety of changes can occur in the outer cell membrane after the injury, including morphological and structural changes, blebs and vesiculation, or damage or release of lipopolysaccharides [45]. These changes can alter membrane permeability, causing the outflow of periplasmic enzymes and sensitivity to hydrophobic compounds, dyes or surfactants. Such injury can be quickly repaired during enrichment and the bacteria recovered [45, 46]. Low numbers of bacteria (below the detection level), and the temporary loss of culturability of injured cells may explain why *Salmonella* enumeration was significantly reduced after chilling using direct enumeration, but no change in prevalence was observed when a pre-enrichment step was used.

Smith *et al.* [21], evaluated *Salmonella* prevalence and cross contamination during immersion chilling in a pilot scale chiller. These researchers used split carcass halves with one half of each pair as the control while the other served as the treatment. Smith *et al.* [21] found a 58% reduction of the number of *Salmonella* positive halves that were directly contaminated (24/24 reduced to 10/24), but an increase from 0 to 25% *Salmonella* positive halves exposed to cross-contamination. This finding may explain contradictory results reported by other authors where *Salmonella* prevalence increases during immersion chiller [27, 47-49] or show no change at all post-chill [16, 48, 50, 51].

Only a few publications have addressed the effect of air chilling on *Salmonella*. Some authors have reported that air chilling of poultry has no effect in numbers or prevalence of *Salmonella* [10, 14, 15]. Sanchez *et al.* [33] reported lower prevalence of *Salmonella* and *Campylobacter* on carcasses in a commercial air-chilling system compared with immersion chilling, but they did not include pre-chill *Salmonella* prevalence. In addition, these researchers compared broilers from different farms and geographical locations, which would likely vary in initial microbial numbers.

In the present study air chill carcasses were dry with apparently shrunken skin, which could have an effect on the recovery of bacteria post chill. To test this hypothesis, subsets of carcasses were randomly selected, and the numbers from the same carcasses were compared using the whole carcass rinse (WCR) and breast skin maceration technique. The results for recovery of *E. coli*, coliforms, and *Campylobacter* from these carcasses are presented in Table 2. When skin maceration was used, chilling method had no significant effect on the recovery of *E. coli*, coliforms, and *Campylobacter* ($P < 0.05$). Also, no significant difference in the bacteria number per sample unit (mL or g) was

observed for WCR and skin maceration. These data do not support the hypothesis that differences in the skin surface between chilling methods impact the recovery of bacteria, therefore the combination of low temperature and drying of the skin during air chilling is the most probable cause of bacteria injury and loss of culturability (death or viable but non culturable state). Under normal chilling conditions, the surface of the air chilled carcasses is exposed to a lower cooling temperature for a longer period of time than immersion chilled carcasses. Oosterom *et al.* [32] showed that *Campylobacter* is very sensitive to drying and ca not survive on dry surfaces. In experiments with or without forced air during chilling, it has been shown that decreasing temperatures during air chilling did not have a significant effect on the reduction of *Campylobacter* on pig skin (3.51 vs. 3.18 log cfu/cm^2, pre- and post-chill respectively), but that drying is a decisive factor when forced air is incorporated (3.52 vs. 1.00 log cfu/cm^2, pre- and post-chill respectively).

During immersion chilling, bacteria are washed off from the carcasses, and the bacteria numbers in the chill water seem to equilibrate [52]. In the present experiment, chilling water samples averaged 2.9, 3.1, and 2.7 Log cfu/mL for *E. coli*, coliforms, and *Campylobacter*, respectively, and are similar to those previously reported by Northcutt *et al.* [52].

Analyses of the data from the present study demonstrate that air and immersion chilling, without any chemical intervention, are microbiologically equivalent. In our study, bacterial reductions of up to 1 log unit can be obtained for *E. coli*, coliforms, and *Campylobacter* with dry air or immersion chilling. Data from the present study show that chilling method had no effect on any of the microbial populations studied.

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TABLE 2.1. Numbers (means ± SEM) of *E. coli*, coliforms, *Campylobacter* and *Salmonella* recovered from carcasses before and after air or immersion chilling.

	Escherichia coli		**coliforms**	
	Air n=32	**Immersion n=32**	**Air n=32**	**Immersion n=32**
Pre chilling	3.4 ± 0.1^{x}	3.5 ± 0.1^{x}	3.6 ± 0.1^{x}	3.8 ± 0.1^{x}
Post chilling	2.4 ± 0.1^{y}	2.6 ± 0.1^{y}	2.7 ± 0.1^{y}	2.8 ± 0.1^{y}
Reduction	1.0 ± 0.1	0.9 ±0.1	0.9 ± 0.1	1.0 ± 0.1
	Campylobacter		***Salmonella***	
	Air n=32	**Immersion n=32**	**Air n=18**	**Immersion n=16**
Pre chilling	3.4 ± 0.1^{x}	3.4 ± 0.1^{x}	1.6 ± 0.1^{x}	1.2 ± 0.2
Post chilling	2.1 ± 0.2^{by}	2.4 ± 0.1^{ay}	0.7 ± 0.2^{y}	0.6 ± 0.2
Reduction	1.4 ± 0.1	1.0 ± 0.1	1.0 ± 0.2	0.6 ± 0.3

$^{a-b}$Means ± SEM (Log cfu/mL rinsate) in a row under a subheading without common superscripts are significantly different ($P < 0.05$).

$^{x-y}$Means ± SEM (Log cfu/mL rinsate) in a column under a subheading without common superscripts are significantly different ($P < 0.05$).

TABLE 2.2: Numbers (means ± SEM) of *E. coli*, coliforms and *Campylobacter* recovered from carcasses after air or immersion chilling, using whole carcass rinse or breast skin maceration technique.

	***Escherichia coli*[1]**		
	air chilling	immersion chilling	Probability (chilling)[2]
Whole carcass rinse	2.5 ± 0.2	2.8 ± 0.2	0.2932
Breast skin maceration	3.0 ± 0.3	2.7 ± 0.1	0.4001
Probability (sampling method)[3]	0.0761	0.8835	
	coliforms[1]		
	air chilling	immersion chilling	Probability (chilling)[2]
Whole carcass rinse	2.8 ± 0.2	2.9 ± 0.2	0.6685
Breast skin maceration	3.1 ± 0.3	3.0 ± 0.2	0.6933
Probability (sampling method)[3]	0.1743	0.4777	
	***Campylobacter*[1]**		
	air chilling	immersion chilling	Probability (chilling)[2]
Whole carcass rinse	2.3 ± 0.1	2.3 ± 0.3	0.9141
Breast skin maceration	2.0 ± 0.3	2.0 ± 0.1	0.9338
Probability (sampling method)[3]	0.3082	0.2098	

[1] Log cfu/mL for rinses and Log cfu/g for skin maceration; N=8.
[2] ANOVA test p-value of the difference between chilling methods.
[3] Paired T-test of the difference "Breast skin maceration - whole carcass rinse".

CHAPTER 3

EFFECT OF IMMERSION OR DRY AIR CHILLING ON BROILER CARCASS MOISTURE RETENTION AND BREAST FILLET FUNCTIONALITY[2]

[2] R. Huezo, D. P. Smith, J. K. Northcutt, D. L. Fletcher. Submitted to Journal of Applied Poultry Research

SUMMARY

A study was conducted to investigate the effect of chilling method on broiler carcass skin color, moisture retention, breast fillet quality and functionality. One hundred fifty eviscerated broilers carcasses were removed from a commercial processing line prior to chilling, transported to the laboratory, weighed and chilled by dry air or immersion in ice water. Post-chill carcasses were weighed for moisture uptake, and held on ice at 4 ^{o} C for 24 h. After storage, fillets were deboned, marinated and cooked. Carcass skin color was measured immediately after chilling and after storage. Fillet color was measured on the medial surface prior to marination and after cooking. Cooked fillets shear values were determined using an Allo-Kramer multiple blade. After 150 min of air chilling, carcasses lost 2.5% of pre-chill weight, and weight loss ranged from 2.2% to 3.5%. Water absorption during immersion averaged 9.3% of the pre-chill weight, but varied widely with a range of 3.4% to 14.7%. Immediately after chilling, breast skin for immersion chilled (IC) carcasses was significantly lighter (higher L*), less red (lower a*), and less yellow (lower b*) than the breast skin color for air chilled (AC) carcasses. Storage time improved appearance of AC carcasses. Raw and cooked fillet color, fillet marination pick-up, and cooked fillet tenderness were not affected by chilling method. Cook yield for fillets deboned from IC carcasses was significantly lower than fillets from AC carcasses.

DESCRIPTION OF PROBLEM

During commercial poultry processing, eviscerated carcasses are chilled by immersion or cold-air blast primarily to reduce microbial growth [1-6]. In the U.S., immersion chilling has traditionally been the most common method of cooling poultry carcasses because it is both efficient and economical [2, 6]. However, air chilling is gaining in popularity because of the limited availability of water, wastewater discharge restrictions, increasing concerns over cross-contamination with immersion chilling, and changes in the U.S. federal regulations on carcass moisture retention [7]. In addition, air chilled poultry may be exported to countries in the European Union (EU) where immersion chilled poultry is not viewed favorably [8-10]. This is important to the U.S. because the EU poultry market has been estimated to be worth $1.2 billion annually and additional countries are requesting membership every year. Thus, acceptance of U.S. poultry in the EU would have a significant economic impact on the poultry industry.

In 2001, the USDA published a regulation on moisture retention in post-eviscerated poultry which requires establishments to do the following: 1) Document the amount of water retained in chilled poultry carcasses and carcass parts; 2) Disclose the amount of water in the poultry product as a result of processing on the product label; and 3) Demonstrate that absorbed water is “an unavoidable consequence of processing required to meet the pathogen reduction performance standards” [7]. The regulation also emphasizes that livestock carcasses are cooled by evaporative air chilling where water is misted to accelerate heat removal but carcasses do not gain moisture. This same ruling

states that retained moisture should be documented to provide consumers with information necessary to make adequate purchase decisions [7].

Previous research on immersion chilled poultry has shown that the majority of the water is held between the skin and the meat and drips from the carcass during cut-up and deboning [11-13]. Young and Smith [14] compared moisture retention of dry air and immersion chilled broiler carcasses and found that air chilled carcasses lost 0.68% of their pre-chill weight while immersion chilled carcasses gained 11.7% moisture. They also reported that immersion chilled carcasses lost 5.7% moisture during cut-up and another 2.1% during storage. However, these researchers air chilled carcasses in individual bags which likely minimized evaporative weight loss [14].

Research on immersion chilling has reported that while carcass appearance is improved, the excessive drip loss, higher thaw loss, higher transportation cost, and cooking loss are undesirables consequences compared to air chilling [1-3, 15, 16]. Immersion chilling is also a water intensive process, requiring about 2.6 L per bird to fill the chill tank at shift start-up and additional overflow of 1.9 L per bird. According to recent surveys, the average water usage for poultry processing in the U.S. is about 26.0 L/bird [17, 18]. With water and sewer costs averaging about $4 /3785 L, immersion chilling of poultry has become an expensive process.

Previous review articles has shown advantages and disadvantages for both air and immersion chilling of poultry; however, in many cases the details of the methods are incomplete [2, 3, 5, 6, 19-21]. Therefore, the present study was conducted to evaluate the effects of immersion and air chilling of poultry carcasses on weight change, skin color, raw fillet color, marination pick-up, fillet cook loss, and fillet tenderness.

MATERIALS AND METHODS

Broiler carcasses procurement:

During each of three replications, 50 eviscerated broiler carcasses were removed from a commercial processing line prior to chilling, placed into coolers and transported to the laboratory. Carcasses were tagged on the wing [22] and weighed. After weighing, carcasses were randomly assigned to one of two chilling treatments: immersion or air chilling (Figure 1).

Chilling treatments:

Carcasses were chilled by immersion in ice water or by cold air. Immersion chilled carcasses were immersed in 133 L of a mixture of ice and tap water (approximately 0.6^{o} C) in a prototype tumble chiller. The paddles in the tumble chiller were operated at 4 rpm for the duration of the 50 min chill. After immersion chilling (IC), carcasses were hung in shackles and allowed to drip for 5 min. Air chill (AC) carcasses were cooled for 150 min. Air was distributed directly into the abdominal cavity of each carcass by means of ducts that provided a continuous flow (3.5 m/s) of cold air (approximately -1.1^{o} C).

Post-chill carcasses were weighed and breast skin color was measured using a Minolta colorimeter [23]. Skin color measurements were made in triplicates on the lateral body apterium (the area between the pectoral and lateral body tracts). After measuring color, carcasses were individually bagged and held on ice in a 4^{o} C cold room for approximately 24 h. For each treatment and replication, one to three carcasses were

selected for continuously monitoring internal breast temperature with a Cox® recorder [24].

Deboning, marination and cooking:

After 24 h of post-chill storage, carcass skin color was measured again using the colorimeter [25]. The left and right breast fillets (*Pectoralis*) were manually removed, and individually tagged [26] and weighed. Fillet color was measured and fillets were pooled for marination. Marination [27] was conducted for 20 min under vacuum (25 in. of Hg) at 4^{o} C using a pre-chilled (4^{o} C) solution (95% water: 3% salt: 2% sodium tripolyphosphate). Marinade was added to the tumbler at 20% (wt:wt) of the raw weight. After marination, fillets were weighed individually and placed on aluminum trays (medial surface down) for cooking. Fillets were cooked at 95^{o} C in steam cooker for 15 min. After cooking, fillets were covered with aluminum foil and allowed to cool to room temperature. Cooked fillets were reweighed to determine cooked yield.

Shear Values:

Shear values were determined according to the method described by Smith *et al.* [28] with modifications. Briefly, this method uses an Allo-Kramer (AK) multiple blade shear cell on an Instron [29] Universal Testing Machine. A 25 mm diameter round sample core was removed from the thickest part of each fillet. Sample cores were weighed to the nearest 0.1 g, and then placed in the shear cell such that the shear blades would impact the sample perpendicular to the orientation of the surface muscle fibers. Samples were sheared using a 500 kg load cell and cross head speed of 500 mm/min.

Shear values are calculated by dividing the sample core weight by the maximum kg shear, and expressed as kilograms of shear per gram of sample.

Color Measurements:

For carcass skin and fillet color, the complete International Commission on Illumination (CIE) system color profile of lightness (L*), redness (a*), and yellowness (b*) was measured using a Minolta Chromameter CR-300 [30]. The colorimeter was calibrated throughout the study using a standard white ceramic tile [31]. Only areas free from obvious defects (bruises, discolorations, hemorrhages, picking damage, or any other condition that might have affected uniform color reading) were selected for color measurements. For fillet color determination, measurements were made on the medial surface (bone side) to avoid breast fillet surface discolorations due to possible over-scalding in the plant.

Statistical Analysis:

All the variables determined during this study are presented in Table 1. For marination pickup, cook yield, shear and color, data were analyzed by ANOVA procedure of the general linear models of SAS software using replication and chilling treatment as the main effects [32]. Main effects and their interactions were tested for statistical significance using the residual error ($P < 0.05$). When the interaction between replication chilling and method was found to be significant, it was used as the error term to test the main effects. A paired t-test from the readings of the same carcass was used to

test the significance of the skin color change between time of chilling and 24 h of refrigerated storage.

RESULTS AND DISCUSSION

Carcass temperature, weight gain/loss during chilling, and skin color:

The internal temperature of the carcasses before starting the chilling process averaged 32.8^{o} C measured in the thickest part of the breast. Carcass temperature decreased 2.8 to 5.0^{o} C during transportation from the processing plant to the experimental facility. Figure 2 shows the temperature decrease curves measured in the thickest part of the breast during air and immersion chilling. Under the conditions of the present experiment, the average time to reach an internal temperature of 4.4^{o} C was 35 and 90 min for immersion and air chilling, respectively. The slow chilling rate of the air chilling system allowed the AC carcasses a 55 min period with a slightly higher mean temperature of 8.3^{o} C. Temperature of the breast muscle during rigor development has been demonstrated to affect meat quality [33-37]. Previous research has indicated that elevated temperatures or slower chilling rates can affect post mortem glycolysis, and ultimate meat texture and functional properties [38-42].

Table 2 shows the changes in broiler carcass weight and skin color immediately after air or immersion chilling and after 24 h of refrigerated storage. Chilling method (air or immersion) significantly affect carcass weight ($P < 0.05$). After 150 min of air chilling, carcasses lost 2.5% of pre-chill weight, and values ranged from 3.5% loss to 2.2% loss. Water absorption during immersion was highly variable, averaging 9.3% of the pre-chill

weight, but ranged form 3.4% to 14.7%. These data agree with other publications where immersion chilled carcasses were found to gain 6% to 12% of the pre-chill carcass weight [4, 12-14, 43-46]. Other publications reported that air chilled carcasses lost up to 3% of their pre-chill weight [4, 12, 42, 44, 47-49]. In the present study, yields for immersion and air chilled carcasses differed by approximately 11.8% (2.5% + 9.3%) and this was slightly lower than the 12.4% previously reported [14].

The high variation in weight change between individual carcasses during immersion chilling was likely the result of processing parameters such as initial water temperature and ratio of water to ice, chiller agitation, evisceration cut and looseness of the skin, degree of exposed flesh, carcass weight and gender (related to amount of fat) [5, 12, 13, 43, 44, 46, 50]. During air chilling only a few variables, such as, chilling time, temperature, air velocity, skin moisture, and carcass size, are the major contributors to evaporative weight losses [11, 19, 49, 51].

Immediately after chilling, the breast skin of IC carcasses were significantly lighter (higher L*), less red (lower a*), and less yellow (lower b*) than AC carcasses ($P<0.05$). Storage time improved the skin appearance of AC carcasses, but skin color after 24 h of storage still differed for the two chilling methods (Table 1). Lightness, redness and yellowness skin values for AC carcasses changed during 24 h of refrigerated storage, but only L* and a* skin values significantly changed for IC carcasses after 24 h of storage. Skin on AC carcasses appeared dried during cooling, and it became more translucent when compared to the IC carcasses. As a result, appearance of the skin of AC carcasses was darker than IC carcasses because underlying muscle was visible through the skin. Dryness affects carcass light reflectance and skin color, because the skin

becomes thin and the background color (breast muscle) increases the redness and yellowness. Other factors that contribute to the difference in color between chilling methods is the loss of some of the epidermis during immersion chilling due to agitation, washing effect, and carcass to carcass contact.

Mielnik *et al.* [48] reported lower L* values and higher b* values for AC carcasses than carcasses cooled with evaporative air chilling. These authors suggested that water spraying during evaporative air chilling prevented the carcass skin from becoming dehydrated, thus ensured a lighter color. Lyon and Cason [52] compared pre- and post- immersion chill carcass skin color and found that chilling significantly increased the skin lightness (L*=61.6 pre-chill vs 64.6 post-chill). In the present study, post-chill L* was higher than the values reported by Lyon and Cason [52]. This likely occurred because Lyon and Cason [52] used a shorter chilling time (30 vs 50 min) and measured breast skin color on a different carcass location.

Immediately after chilling, the skin of the IC carcasses was 13.5 units lighter than the skin of AC carcasses. After 24 h of refrigerated storage, skin lightness of AC carcasses increased while the opposite was observed in the IC carcasses skin color (lower L^*). The difference in $L^*_{skin\ 24h}$ between chilling methods was 6.4 units. When initial post-chill redness and yellowness ($a^*_{skin\ 0h}$, $b^*_{skin\ 0h}$) where compared to values measured after 24 h storage ($a^*_{skin\ 24h}$, $b^*_{skin\ 24h}$), AC carcasses were less red and less yellow after storage (lower $a^*_{skin\ 24h}$ and $b^*_{skin\ 24h}$) while IC carcasses were more red and more yellow after storage (Table 2). The change in color of the IC carcasses agrees with findings reported by Petracci and Fletcher [53], where a reduction in lightness, a slight decrease in redness, and no significant change in yellowness occurred during storage. Color of AC carcasses

changed after storage because of differences in moisture content of the skin. Previous research has shown that AC carcasses immediately after chilling had a lower water activity than immersion chilled carcasses, but similar water activity was found between carcasses chilled using either method after 4 h of storage [54]. The increase in moisture after storage affected light reflectance and therefore the skin color measurements.

Fillet color, marination pick-up, cook yield and tenderness:

Table 3 shows the effect of broiler carcass chilling method on raw and cooked breast fillet color. Chilling method did not affect the color of raw or cooked breast fillets ($P>0.05$). These data agree with previous research which reported no significant difference in L*, a* and b* values of raw breast fillets between air or immersion chilling [55].

Table 4 shows the effect of chilling method on marination pickup, cook yield and cooked fillet shear values. Marination pick-up was not affected by chilling treatment ($P>0.05$). When cook yield was calculated as a percentage of the marinated weight (cook yield 1) or pre-marination weight (cook yield 2), yield of IC carcasses was significantly lower than that of AC carcasses ($P < 0.05$). AC fillets lost 1.3% and 2.2% less weight than IC carcasses from marinated weight to cooked weight (cook yield 1) and from raw weight to cooked weight, respectively (cook yield 2). During immersion chilling, fat and body tissue are lost, and moisture is absorbed [56]. This water is then lost during cooking, which reduces cook yield. Hale and Stadelman [44] reported that AC carcasses lost less weight (2.6%) from the time of evisceration to cooking than IC carcasses. Sanders [43] used a dye tracer to demonstrate that the primary route of water entry to areas between

the skin and muscle was through carcass openings. In particular, this author noted that water entered the most exposed areas of the carcasses near the keel tip and over the clavicle. When agitation was provided during IC, the extent of dyed muscle surface and water penetration between the skin and the muscle was significantly increased [43].

AK shear values were similar for cooked fillets from carcasses chilled using either method (Table 4). Previous research has shown that resolution of rigor and tenderization occurs 4 to 6 h post mortem [36, 57-60]. DeFremery and Pool [60] demonstrated that chicken meat aged on the carcass for 4 h or more at 0º C to 40º C had comparable tenderness. Dunn *et al.* [39] compared carcass quality after either fast AC (–12°C for 50 min) or normal AC (80 min at 0°C + 2 h at 4° to 6°C) and reported no significant difference in cooked fillet shear force or cook yield between chilling methods. Data from the present study agrees with this previous research [39]. In more recent studies, Perumalla *et al.* [61] reported that chilling method (air and immersion) did not affect broiler breast fillet marinade pick-up, cook loss and tenderness. However, these authors used static IC with a reported 4% water absorption, compared to the 9.3% of moisture absorption found in the present experiment.

Correlation analysis:

Pearson's correlation coefficients for initial carcass weight, moisture gain/loss after chilling, marination pick-up, raw fillet color, and cook yield are presented in Table 5. A significant positive correlation was found for initial carcass weight and weight gain (r=0.31) during IC and weight loss (r=-0.83) during AC. The changes in weight are related to the initial size and surface area, accounting for moisture gain or loss due to

evaporation. Weight gain during IC was also related to cook yield 1 (r=0.28) and cook yield 2 (r=0.37), but a similar relationship was not observed for AC carcasses. Moisture gain during IC was negatively correlated with breast fillet lightness (r=-0.31). This is likely due to the removal of water soluble proteins (myoglobin, hemoglobin, and cytocrome C) which provide color [55]. A significant correlation was found for weight loss of AC carcasses and L^*_{raw} (r= -0.31), and for weight loss of AC carcasses and a^*_{raw} (r= 0.31). As weight loss of AC carcasses increased, the L^*_{raw} value decreased while the a^*_{raw} increased. This may be attributed to evaporative losses of moisture from carcass components and the negative correlation between lightness and redness previously reported by Qiao *et al.* [62]. Significant correlations were also found between L^*_{raw} and cook yield, a^*_{raw} and marination pick-up, shear and cook yield, and between marination pick-up and cook yield. However, chilling method did not affect the direction of these correlations.

CONCLUSIONS AND APPLICATIONS

1. Chilling method affects carcass appearance and yield, but appearance is significantly improved during refrigerated storage (4^{o} C).
2. Raw or cooked meat color is not affected by chilling method.
3. A slower chilling rate during air chilling, compared with immersion chilling, did not affect meat tenderness after 24 h of aging.
4. Fillets functionality was improved by air chilling (higher cook yield).
5. The lower cook yield of immersion chilled breast fillets resulted from lost moisture that had previously been absorbed during chilling.
6. Processors selling whole carcasses or bone-in carcass parts may want continue to use immersion chilling as their primary cooling method, but further processing operations that debone meat may find that air chilling is a suitable alternative for cooling poultry carcasses because fillet color, marination yield and tenderness are not affected, but cook yield is improved.

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TABLE 3.1. Description of variables for whole carcasses and breast fillets

Parameter	Description
Moisture uptake/loss	((post-chill weight / pre-chill weight) - 1)
Marination pick-up	((marinated fillet weight / non-marinated weight) - 1)
Cooking loss 1	((cooked fillet weight / marinated weight) - 1)
Cooking loss 2	((cooked fillet weight / pre-marination breast weight) - 1)
Shear value	Total shear (kg) / core weight (g)
$L^*_{\text{skin 0h}}$	Value of lightness of the skin post-chill
$a^*_{\text{skin 0h}}$	Value of redness of the skin post-chill
$b^*_{\text{skin 0h}}$	Value of yellowness of the skin post-chill
$L^*_{\text{skin 24h}}$	Value of lightness of the skin after 24h of storage at 4^o C in a plastic bag
$a^*_{\text{skin 24h}}$	Value of redness of the skin after 24h of storage at 4^o C in a plastic bag
$b^*_{\text{skin 24h}}$	Value of yellowness of the skin after 24h of storage at 4^o C in a plastic bag
L^*_{Change}	$L^*_{\text{chilled}} - L^*_{\text{24h}}$
a^*_{Change}	$a^*_{\text{chilled}} - a^*_{\text{24h}}$
b^*_{Change}	$b^*_{\text{chilled}} - b^*_{\text{24h}}$
$L^*_{\text{fillet raw}}$	Value of lightness of the medial surface of raw fillets
$a^*_{\text{fillet raw}}$	Value of redness of the medial surface of raw fillets
$b^*_{\text{fillet raw}}$	Value of yellowness of the medial surface of raw fillets
$L^*_{\text{fillet cooked}}$	Value of lightness of the medial surface of cooked fillets
$a^*_{\text{fillet cooked}}$	Value of redness of the medial surface of cooked fillets
$b^*_{\text{fillet cooked}}$	Value of yellowness of the medial surface of cooked fillets

TABLE 3.2. Moisture retention/loss and skin color immediately after chilling and after 24 h of refrigerated storage for immersion and air chilled broiler carcasses

Variable[1]	Air	Immersion	*P*[2]
Moisture uptake/loss (%)	-2.5±0.00	9.3 ± 0.05	0.0073
$L^*_{skin\ 0h}$[3]	57.1±0.47	70.6 ± 0.27	< 0.0001
$a^*_{skin\ 0h}$	2.0±0.11	0.5 ± 0.09	< 0.0001
$b^*_{skin\ 0h}$	5.1±0.35	-0.3 ± 0.29	< 0.0001
$L^*_{skin\ 24h}$[4]	61.4 ± 0.47	67.8 ± 0.32	< 0.0001
$a^*_{skin\ 24h}$	1.5 ± 0.12	1.0 ± 0.10	0.0008
$b^*_{skin\ 24h}$	1.0 ± 0.28	0.0 ± 0.21	0.0067
L^*_{change}[5]	-4.4 ± 0.52	2.8 ± 0.33	< 0.0001
a^*_{change}	0.5 ± 0.10	-0.5 ± 0.10	< 0.0001
b^*_{change}	4.1 ± 0.37	-0.4 ± 0.24	< 0.0001

[1]Mean ± Standard error.
[2]Probability values from ANOVA.
[3]Lightness ($L^*_{skin\ 0h}$), redness ($a^*_{skin\ 0h}$) and yellowness ($b^*_{skin\ 0h}$) of the skin immediately post-chill.
[4]Lightness ($L^*_{skin\ 24h}$), redness ($a^*_{skin\ 24h}$) and yellowness ($b^*_{skin\ 24h}$) of the skin 24 h post chill.
[5]$L^*_{change} = L^*_{skin\ 0h} - L^*_{skin\ 24h}$, $a^*_{change} = a^*_{skin\ 0h} - a^*_{skin\ 24h}$, $b^*_{change} = b^*_{skin\ 0h} - b^*_{skin\ 24h}$.

TABLE 3.3. Effect of broiler carcass chilling method on raw and cooked breast fillet color

Parameter[1]	Air	Immersion	*P*[2]
$L^*_{\text{fillet raw}}$[3]	49.1 ± 0.38	49.3 ± 0.42	0.6300
$a^*_{\text{fillet raw}}$	3.4 ± 0.10	3.1 ± 0.11	0.5228
$b^*_{\text{fillet raw}}$	6.1 ± 0.18	6.1 ± 0.19	0.9797
$L^*_{\text{fillet cooked}}$[4]	78.6 ± 0.12	78.5 ± 0.14	0.3002
$a^*_{\text{fillet cooked}}$	2.0 ± 0.06	2.0 ± 0.06	0.8940
$b^*_{\text{fillet cooked}}$	11.2 ± 0.12	11.5 ± 0.15	0.4360

[1]Mean ± Standard error.
[2]Probability values from ANOVA.
[3]Lightness ($L^*_{\text{fillet raw}}$), redness ($a^*_{\text{fillet raw}}$) and yellowness ($b^*_{\text{fillet raw}}$) of the medial side of raw fillets.
[4]Lightness ($L^*_{\text{fillet cooked}}$), redness ($a^*_{\text{fillet cooked}}$) and yellowness ($b^*_{\text{fillet cooked}}$) of the medial side of cooked fillets.

TABLE 3.4. Effect of broiler carcass chilling method on raw breast fillet marination pick-up, and cooked fillet yield and shear

Parameter[1]	Air	Immersion	*P*[2]
Marination pick-up (%)	20.2 ± 0.06	19.2 ± 0.05	0.1872
Cook Yield 1 (%)[3]	67.7 ± 0.00	66.4 ± 0.00	0.0011
Cook Yield 2 (%)[4]	81.3 ± 0.00	79.1 ± 0.00	<0.0001
Cooked fillet Shear (Kg/g)	2.2 ± 0.10	2.8 ± 0.13	0.3962

[1]Mean ± Standard error.
[2]Probability values from ANOVA.
[3]((cooked breast weight / marinated breast weight) - 1).
[4]((cooked breast weight / pre-marination breast weight) - 1).

TABLE 3.5. Pearson's correlation coefficients for carcass weight gain/loss during chilling, marination pick-up, raw fillet color, cooked fillet yield and shear force

Parameter	Chilling method	Weight gain/loss	Marination pickup	Cook yield 1[2]	cook yield 2[3]
Initial carcass weight	Air	-0.83*	---	---	---
	Immersion	0.31*	---	---	---
Moisture uptake/loss	Air	---	-0.02	-0.12	-0.11
	Immersion	---	0.16	0.28*	0.37*
$L^*_{\text{fillet raw}}$[1]	Air	0.29*	0.01	-0.71*	-0.58*
	Immersion	-0.31*	-0.11	-0.48*	-0.49*
$a^*_{\text{fillet raw}}$	Air	0.31*	0.46*	-0.07	0.35*
	Immersion	-0.09	0.28*	-0.17	0.12
$b^*_{\text{fillet raw}}$	Air	-0.05	-0.14	0.05	-0.08
	Immersion	-0.11	-0.2	-0.14	-0.3*
Shear	Air	0.08	-0.02	-0.53*	-0.48*
	Immersion	0.04	0.02	-0.26*	-0.19
Raw weight[4]	Air	---	-0.6*	0.43*	---
	Immersion	---	-0.51*	0.52*	---
Marination pickup	Air	---	---	-0.34*	0.61*
	Immersion	---	---	-0.30*	0.63*

[3]Lightness ($L^*_{\text{fillet raw}}$), redness ($a^*_{\text{fillet raw}}$) and yellowness ($b^*_{\text{fillet raw}}$) of the medial side of raw fillets.
[2]((cooked breast weight / marinated breast weight) - 1).
[3]((cooked breast weight / pre-marination breast weight) - 1).
[4]pre-marination fillets weight.
*Significant at 5% level.

FIGURE 1. Experimental design for each of three replications.

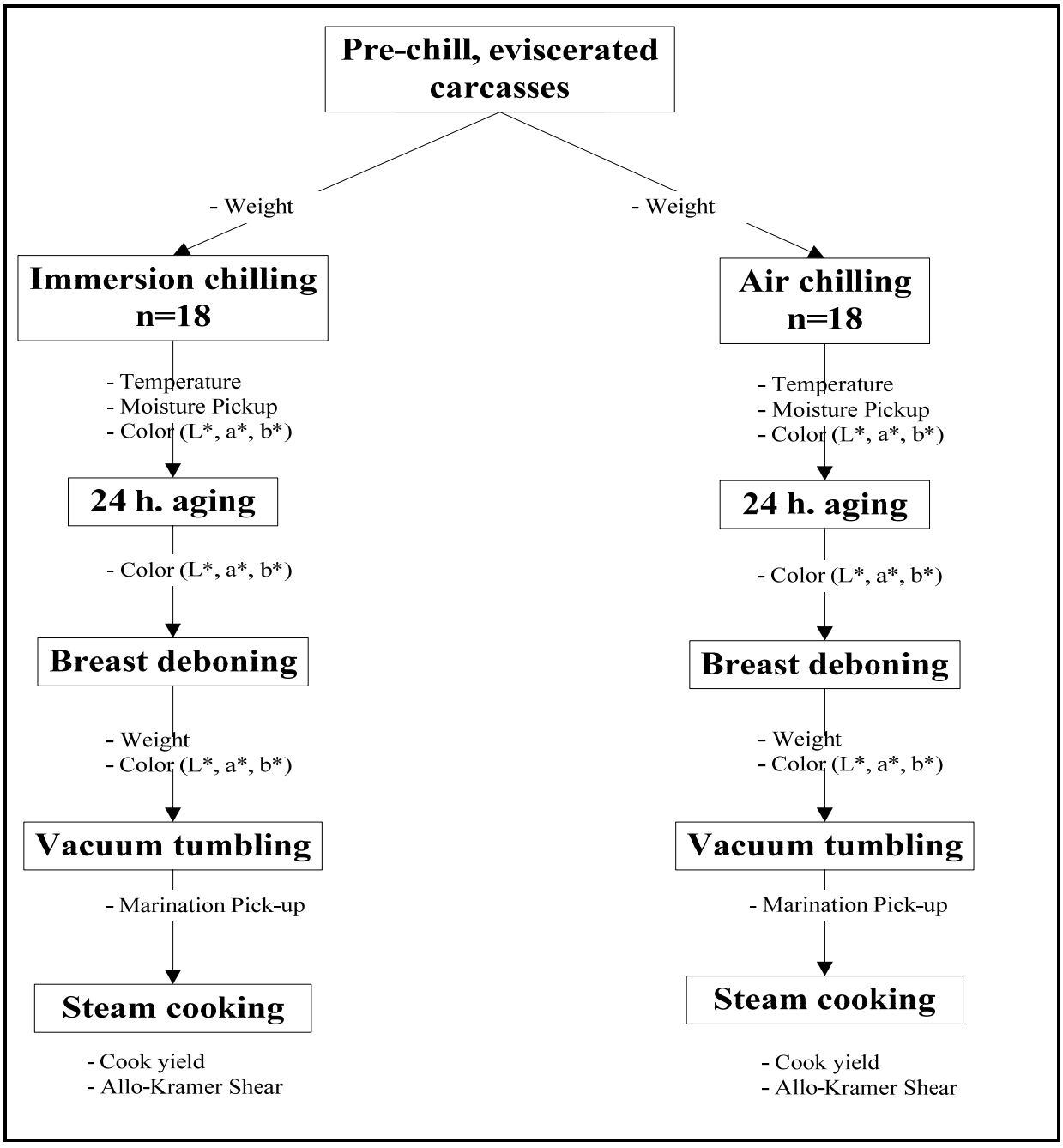
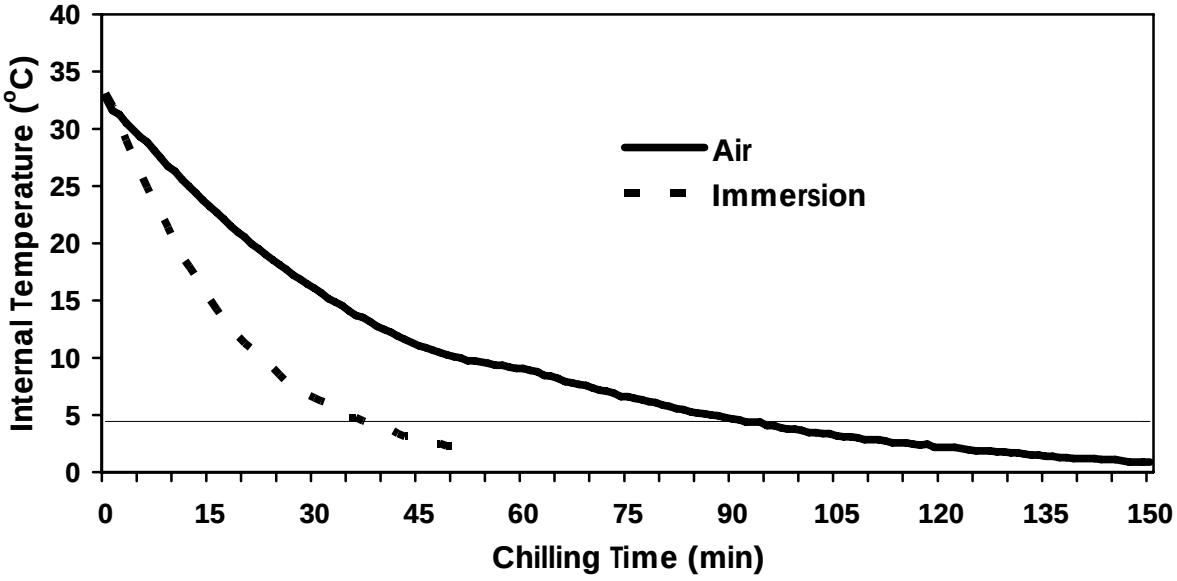


FIGURE 2. Temperature of breast muscle of chicken carcasses during air and immersion chilling



CHAPTER 4

EFFECT OF CHILLING METHOD AND DEBONING TIME ON BROILER BREAST FILLET QUALITY[3]

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SUMMARY

A study was conducted to determine the effects of chilling method and post-mortem aging time on broiler breast fillet quality. One hundred-fifty eviscerated broiler carcasses were removed from a commercial processing line prior to chilling and transported to the laboratory. Half of the carcasses were chilled by dry air, while the other half was chilled by water immersion. Immersion chilled (IC) carcasses were divided into 3 groups (0, 1.67 and 24 h of aging time) based on post-mortem fillet aging time on the carcass. Air chilled (AC) carcasses were divided into two groups based on fillets aging time (0 and 24 h). Because AC requires more time to bring carcass temperature down to required levels, fillets removed immediately after chilling (0 h) were aged for the same length of time as the 1.67 h IC fillets. Average pH values of IC and AC fillets were similar when fillets were aged for the same length of time post-mortem. Method of chilling had no effect on raw breast fillet color; however, post-mortem aging time had a slight but significant effect on fillet lightness. Shear values of IC fillets removed 0 and 1.67 h after chilling were similar and corresponded to sensory panel categories of “slightly tough” to “tough” (> 8 kg/g). Shear values of AC fillets deboned at 0 h (8.4 kg/g) were lower than IC fillets (10.3 kg/g) aged for the same length of time (1.67 h). After 24 h of aging, shear values for IC and AC fillets were < 8 kg/g and corresponded to sensory panel categories of “tender” to “very tender”. Cook yield of AC fillets was significantly higher than cook yield of IC fillets for all deboning times. Results show that air chilling has an effect on rigor mortis, but post-chill aging time is always required to maximize the proportion of tender meat.

DESCRIPTION OF PROBLEM

According to the National Chicken Council, approximately 8.9 billion broiler carcasses were processed in the U.S. in 2005. Of these, only 7.5% were marketed as whole carcasses, while the remaining 92.5% were further processed [1, 2]. Further processing begins immediately after chilling with carcasses cut into forequarters and hindquarters. Most of the hindquaters are marketed as fresh or frozen bone-in parts. Wings and breast fillets are removed from forequaters and used in further processed products or marketed as fresh skinless deboned products [3]. Further processed carcass parts depend on tenderness and apperance for consumer acceptability. Early deboning of fillet (prior to rigor mortis completion) is the primary cause of increased incidence of tough broiler breast meat [3].

Several studies have been conducted to determine the optimum post mortem aging time on the carcass to prevent breast fillets toughness. Tenderness of broiler breast meat typically requires 4 to 6 h of aging time before deboning [4-16]. Aging fillets before deboning allows the development of rigor mortis and meat tenderization [8, 12, 17, 18]. Aging carcasses or breast halves is costly because of space required to store carcasses, energy cost, and logistics of moving product. Many processors would prefer to debone fillets immediately after chilling which would be 30 to 50 min of dwell time for immersion [19, 20] and 90 to 150 min for air chilling systems [21, 22]. To obtain the 4 to 6 h optimal aging time, processors currently must store intact carcasses or forequarters at refrigerated temperatures (< 4 C) an additional 2.5-4.5 h before deboning [23].

Temperature of the breast muscle during post mortem aging has been demonstrated to affect fillet quality [8, 24-28]. Previous studies have indicated that elevated temperatures or slower chilling rates may affect post mortem glycolysis, and ultimate meat texture and functional properties [29-37]. Huezo *et al.* [38], demonstrated that chilling method (air or immersion) had no effect on breast fillet tenderness when fillets are deboned 24 h post-chill. However, there is no information available comparing breast fillet functionality of early deboned broiler carcasses chilled by either immersion or air. Therefore, the present study was conducted to evaluate the effect of deboning time and chilling method (immersion or air) on breast fillet pH, color, cook loss, and tenderness.

MATERIALS AND METHODS

Broiler carcasses procurement:

During each of three replications, 50 eviscerated broiler carcasses were removed from a commercial processing line prior to chilling, placed into coolers and transported to the laboratory. Carcasses were tagged on the wing [39] and weighed. After weighing, carcasses were randomly assigned to one of two chilling treatments: immersion or air chilling (Figure 1).

Chilling treatments:

Carcasses were chilled by immersion in ice water or by cold air without any water spray (dry). Immersion chilled carcasses were immersed in 133 L of a mixture of ice and

tap water (approximately 0.6^{o} C) in a prototype tumble chiller. The paddles in the tumble chiller were operated at 2 rpm for the duration of the 50 min chill. After immersion chilling (IC), carcasses were hung in shackles and allowed to drip for 5 min. and then placed in three groups of nine carcasses per group and assigned to 0 h, 1.67 h, and 24 h post chill aging time before deboning (Figure 1.). Air chill (AC) carcasses were cooled for 150 min. Air was distributed directly into the abdominal cavity of each carcass by means of specially modified channels that provided a continuous flow (3.5 m/s) of cold air (approximately -1.1^{o} C). Air chilled carcasses were placed into two deboning times, 0 h and 24 h post chill. Because AC requires more time, AC fillets deboned immediately after chilling (0 h) were aged for the same length of time as the 1.67 h IC fillets.

Post-chill carcasses were individually bagged and held on ice in a 4^{o} C cold room until deboning. For each treatment and replication, one to three carcasses were selected for continuously monitoring internal breast temperature with a Cox® recorder [40].

Deboning and cooking:

At each deboning time, the left and right breast fillets (*Pectoralis*) were manually removed and individually tagged. From each pair of fillets, one was used for pH and color determination, while the other fillet was cooked and used for yield evaluation and tenderness. Fillet color was measured [41] on the medial side (bone side). Fillets selected for cook yield and shear determination were weighed individually, placed on aluminum trays and cooked at 95^{o} C in a steam cooker for 15 min. After cooking, fillets were covered with aluminum foil, allowed to cool to room temperature, and then reweighed to determine cooked yield.

Shear Values:

Shear values were determined according to the method described by Smith *et al.* [42] with modifications. Briefly, this method uses an Allo-Kramer (AK) multiple blade shear cell on an Instron Universal Testing Machine [43]. A 25 mm diameter round core was removed from the thickest part of each fillet. Cores were weighed to the nearest 0.1 g, and then placed in the shear cell such that the shear blades would impact the sample perpendicular to the direction of the surface fibers. Samples were sheared using a 500 kg load cell with cross head speed of 500 mm/min. Shear values are calculated by dividing the sample core weight by the maximum kg shear, and expressed as kilograms of shear per gram of sample.

Color Measurements:

For raw fillet color, the International Commission on Illumination (CIE) system color profile of lightness (L*), redness (a*), and yellowness (b*) was measured using a Minolta Chromameter CR-300 [44]. The colorimeter was calibrated throughout the study using a standard white ceramic tile [45]. Only areas free from obvious defects (bruises, discolorations, hemorrhages, full blood vessels, picking damage, or any other condition that might have affected uniform color reading) were selected for color measurements. For fillet color determination, measurements were made on the medial surface (bone side) to avoid breast fillet surface discolorations due to possible over-scalding in the plant.

pH determination:

Fillet pH was determined on samples which were removed from the cranial area of each breast fillet. Two and one half g samples were mixed with 25 mL of a 5-m*M* iodoacetate solution with 150 m*M* potassium chloride for 30 s. The pH of the homogenate was determined using a pH meter [46] calibrated at pH 4.0 and 7.0 [47].

Statistical Analysis:

Raw fillets pH, raw fillet color, cooked fillet yield and shear were analyzed using an ANOVA procedure of the general linear model of SAS with replication and treatment as the main effects of the model [48]. Treatment mean differences were tested by multiple linear contrasts using the residual error ($P < 0.05$). When the interaction between replication and treatment was found to be significant, it was used as the error term to test linear contrasts. The comparisons of interest were 0 h AC vs 0 h IC (post-chill comparison); 0 h AC vs 1.67 h IC (physiological comparison); and 24 h AC vs 24 h IC (aged comparison).

RESULTS AND DISCUSSION

Table 1 shows the effect of broiler carcass chilling method and deboning time on raw fillet color. Deboning time significantly affected lightness (L*) of breast fillets from both air and immersion chilled carcasses. A significant difference in lightness was observed between immersion chilled (IC) breast fillets deboned immediately after chilling and after 1.67 h post-chill, but no significant change was observed after 1.67 h

post chill ($P > 0.05$). A slight but significant increase in lightness was observed for air chilled (AC) fillets deboned immediately after chilling and after 24 h ($P < 0.05$). An increase in lightness with increased deboning time was previously reported in turkey breast fillets [49]. Petracci and Fletcher [50] reported a reduction in broiler breast fillet lightness with time, but these authors sampled the surface of the fillets under the skin, which may have been affected by moisture absorption during chilling. Papinaho *et al.* [7] reported that deboning time did not affect lightness, redness, or yellowness of air chilled (AC) fillets when color was measured 24 h after deboning. Their findings indicate that any color change of early deboned breast fillets disappears when rigor mortis is completed. Fletcher [51] provided a review of the correlation between poultry breast meat lightness (L*) and breast muscle pH. In general, he suggested that as muscle pH decreases the lightness values increase, with a correlation coefficient between -0.6 and -0.8. Thus, the increased trend in lightness with deboning time observed during the present experiment may be caused by the post-mortem glycolysis and gradual lowering of muscle pH, which affects water holding, surface translucence and muscle reflectivity [51].

The effect of broiler carcass chilling method and deboning time on raw fillet pH, cooked fillet yield and cooked fillet shear values are presented in Table 2. The pH of IC breast fillets deboned 0 h post-chill was significantly higher than the pH of IC fillets deboned 1.67 h or 24 h post-chill. No significant difference in pH was observed for fillets from carcasses deboned 1.67 h and 24 h post-chill ($P > 0.05$). Fillets removed from AC carcasses at 0 or 24 h post-chill had comparable pH values. Post-mortem time for muscle to reach its ultimate pH may be 4 to 6 h [6, 7, 16, 52, 53], but some studies have reported ultimate pH in poultry as early as 2 h post mortem [14, 54]. Different results for time to

reach ultimate muscle pH may be due to differences in initial glycogen levels, bird strain, gender (body size and fat), stunning procedures, and other physiological factors [7].

Deboning at 0 h or 1.67 h after chilling did not affect cook yield or shear values of IC breast fillets, but cook yield and tenderness were improved when fillets were deboned 24 h post-chill ($P<0.05$). Northcutt *et al.* [5] reported that fillets removed immediately after chilling had the lowest cook yield, but cook loss decreased when fillets were aged for 2 h or more. Similar findings have been reported by Liu *et al.* [13]. In another study, Northcutt *et al.* [55] showed that breast fillets lost approximately 0.4% of their weight (drip loss) during the first 6 h post mortem, and approximately 1% after 24 h post mortem. However, carcasses from this study were not immersion chilled and drip loss was inherent moisture. Based on these studies, fillets deboned 24 h post chill should have a greater amount of moisture loss before cooking and a higher cook yield compared with fillets deboned early post mortem. Others studies have contradicted this concept and reported either no differences [7, 56] or a decreased trend in cook yield with latter deboninig times [6, 57, 58]. The conflicting results may be related to differences in breast fillets storage conditions or storage time before cooking.

Biochemical changes in muscles during rigor mortis and the associated effect on fillet pH and tenderness have been studied by a number of researchers [6, 7, 14, 27, 28, 52-54, 56, 59, 60]. In general, as the animal dies from anoxia, the muscle cells continue to respire and to produce and consume ATP. During the perimortem time period (death struggle), muscles continue to contract and relax, depleting cellular oxygen and causing a shift to anaerobic glycolysis until energy reserves are depleted. The primary product of anaerobic glycolysis is lactic acid, which accumulates and decreases muscle pH. At this

point ATP is not available to dissociate the actin and myosin (uncoupling) and they remain complexed as actomyosin. Any pre-rigor cutting or trimming of meat results in a tough product because there is nothing to restrict the shortening of skeletal muscle [27, 34, 61, 62].

Table 3 shows the probabilities values for comparisons between chilling methods at different deboning times for raw fillet pH and color, and cooked fillet yield and shear. When AC and IC fillets were deboned at 0 h post-chill, AC fillets had a significantly lower pH and a significantly higher cook yield ($P<0.05$). This resulted from the difference in post-mortem time and the difference in carcass cooling rates. No significant difference in shear and color was observed between AC and IC fillets. Cook yield of AC fillets deboned 0 h post-chill was 1.9% higher than IC fillets carcasses deboned 1.67 h post-chill. When fillets were deboned 24 h post-chill, cook yield of AC fillets was 2.7% higher than IC ($P<0.05$). The lower cook yield of IC fillets may have resulted from high moisture absorption during chilling and subsequent loss during cooking [38]. No significant difference was observed in pH, raw fillet color, or shear values when IC fillets deboned 1.67 h post-chill were compared with AC fillets deboned 0 h post-chill or when AC and IC fillets were deboned 24 h post-chill. AK shear values of AC fillets deboned 0 h post-chill were nearly 2 units lower than IC fillets deboned 1.67 h post-chill, and this difference is sufficient to be distinguished by a sensory panel [63].

Simpson and Goodwin [64] compared AK multiple blade shear values with sensory measures of tenderness, and concluded that values above 8 kg of force per g of sample corresponded to sensory scores of “slightly tough” to “tough” and values below 8 kg/g corresponded to scores of “tender” to “very tender”. Using these values as reference,

Table 4 shows the distribution of cooked breast fillets shear values according to sensory measures of tenderness for both, chilling method and the deboning times. When IC and AC fillets were deboned at 1.67 h and 0 h post-chill respectively (approximately 3 h post mortem for both treatments), 70% of the IC fillets were considered “slightly tough” to “tough” compared with 44% of the AC fillets. For the same group of carcasses, there were more AC fillets that could be considered “tender” to “very tender” than IC fillets (56% vs. 30%). After 24 h, 100% of the fillets from both chilling treatments had shear values that corresponded to the “tender” to “very tender” sensory category.

Figure 2 shows the pH distribution of raw breast fillets deboned 0 h after AC or after 1.67 h of IC. Immediately after chilling, approximately 70% of IC fillets had pH higher than 5.8, compared to 40% of AC fillets. This suggests an accelerated rigor mortis in the AC fillets compared to the IC fillets because 25% more AC fillets had a pH lower than 5.8.

Figure 3 shows the pH distribution of raw breast fillets deboned 24 h after chilling. There is no difference in the pH distribution between the two chilling methods. This indicates that chilling method has no effect on ultimate pH for carcasses deboned 24 h post-chill, and these data correspond with the texture findings that showed no difference after 24 h of aging.

These results showed that breast fillet color, pH and texture of carcasses with the same postmortem time were not affected by chilling method. Fillets cook yield was higher for AC fillets compared to IC fillets. Air chilling appeared to have an effect on rigor mortis, but post-chill aging time is always required to maximize the proportion of tender meat.

CONCLUSIONS AND APPLICATIONS

1. Cook yield is improved with aging time and air chilling.
2. Fillet lightness increases while pH and shear value decrease with aging time.
3. Breast fillet color, pH and texture of carcasses with the same postmortem time are not affected by chilling method.
4. Air chilling may have an effect on rigor mortis, but post-chill aging time is always required to maximize the proportion of tender meat.
5. Opportunities may exist to combine air chilling with other physical treatments (electrical stimulation) to increase the proportion of tender meat immediately post-chill without compromising the quality of the final product.

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TABLE 4.1. Effect of broiler carcass chilling method and deboning time on raw fillet color

Deboning time	Lightness (L*)		Redness (a*)		Yellowness (b*)	
	Immersion	Air	Immersion	Air	Immersion	Air
0h IC[1]	46.8 ± 0.39[b]	NA[4]	3.0 ± 0.2	NA	5.4 ± 0.3	NA
0h AC and 1.67h IC[2]	48.9 ± 0.56[a]	47.6 ± 0.47[b]	2.8 ± 0.1	3.0 ± 0.2	5.2 ± 0.3	5.3 ± 0.3
24h AC and 24h IC[3]	49.8 ± 0.59[a]	49.9 ± 0.54[a]	2.6 ± 0.1	2.9 ± 0.2	5.1 ± 0.3	5.6 ± 0.3

[1]Carcasses deboned immediately (0 h) after immersion chilling IC.
[2]3 h post mortem = air chilled carcasses (AC) deboned immediately (0 h) post-chill; immersion chilled carcasses (IC) deboned 1.67 h post-chill.
[3]Air and immersion chilled carcasses deboned 24 h post-chill.
[4]Not applicable.
[a-b]Means ± standard error in a column without common superscripts are significantly different ($P < 0.05$).

TABLE 4.2. Effect of broiler carcass chilling method and deboning time on raw fillet pH, and cooked fillet yield and shear

Deboning time	Cook Yield		Allo-Kramer Shear (AK)		pH	
	Immersion	Air	Immersion	Air	Immersion	Air
0h IC[1]	69.2 ± 0.29[b]	NA[4]	10.1 ± 0.59[a]	NA	6.01 ± 0.03[a]	NA
0h AC and 1.67h IC[2]	68.9 ± 0.33[b]	70.8 ± 0.39[b]	10.3 ± 0.67[a]	8.4 ± 0.81[a]	5.84 ± 0.03[b]	5.80 ± 0.02
24h AC and 24h IC[3]	70.1 ± 0.48[a]	72.8 ± 0.38[a]	3.5 ± 0.19[b]	3.2 ± 0.15[b]	5.85 ± 0.02[b]	5.85 ± 0.02

[1]Carcasses deboned immediately (0 h) after immersion chilling (IC).
[2]3 h post mortem = air chilled carcasses deboned immediately (0 h) post-chill; immersion chilled carcasses deboned 1.67 h post-chill.
[3]Air and immersion chilled carcasses deboned 24 h post chill.
[4]Not applicable.
[a-b]Means ± standard error in a column without common superscripts are significantly different ($P < 0.05$).

TABLE 4.3. Probabilities for the cross-comparisons between chilling method and deboning time for raw fillets pH and color, and cooked fillets yield and shear

Deboning times comparisons	Cook Yield	AK shear[4]	pH	L*[5]	a*	b*
0h IC Vs. 0h AC[1]	0.0016	0.2140	0.0124	0.2985	0.9536	0.8055
1.67h IC Vs. 0h AC[2]	0.0005	0.1706	0.5855	0.1388	0.6150	0.9805
24h IC Vs. 24h AC[3]	<0.0001	0.8136	0.9578	0.9032	0.5092	0.1253

[1]Comparison between immersion (IC) and air chilled (AC) carcasses deboned immediately (0 h) chill.
[2]Comparison between immersion (IC) and air chilled (AC) carcasses deboned 1.67h and 0h post-chill respectively.
[3]Comparison between immersion (IC) and air chilled (AC) carcasses deboned 24h post-chill.
[4]Cooked fillet Allo-Kramer shear value.
[5]Lightness (L^*), redness (a^*) and yellowness (b^*) of the medial side of raw fillets.

TABLE 4.4. Distribution of cooked breast fillets shear values according to sensory tenderness, chilling method and deboning time

Sensory Tenderness[1]	1.67h post Immersion Chilling	0h post Air Chilling	24 h post Immersion Chilling	24 h post Air Chilling
"Slightly tough" to "tough"	70%	44%	0%	0%
"Tender" to "very tender"[3]	30%	56%	100%	100%
Probability	0.0541		-----	

[1] According with the multi-blade Allo-Kramer shear value scale and the corresponding sensory tenderness reported by Simpson and Goodwin [64]
[2] "Slightly tough" to "tough" = Allo-Kramer values more than 8.0 kg/g.
[3] "Tender" to "very tender" = Allo-Kramer values less than 8.0 kg/g.

FIGURE 4.1. Experimental design for each of three replications

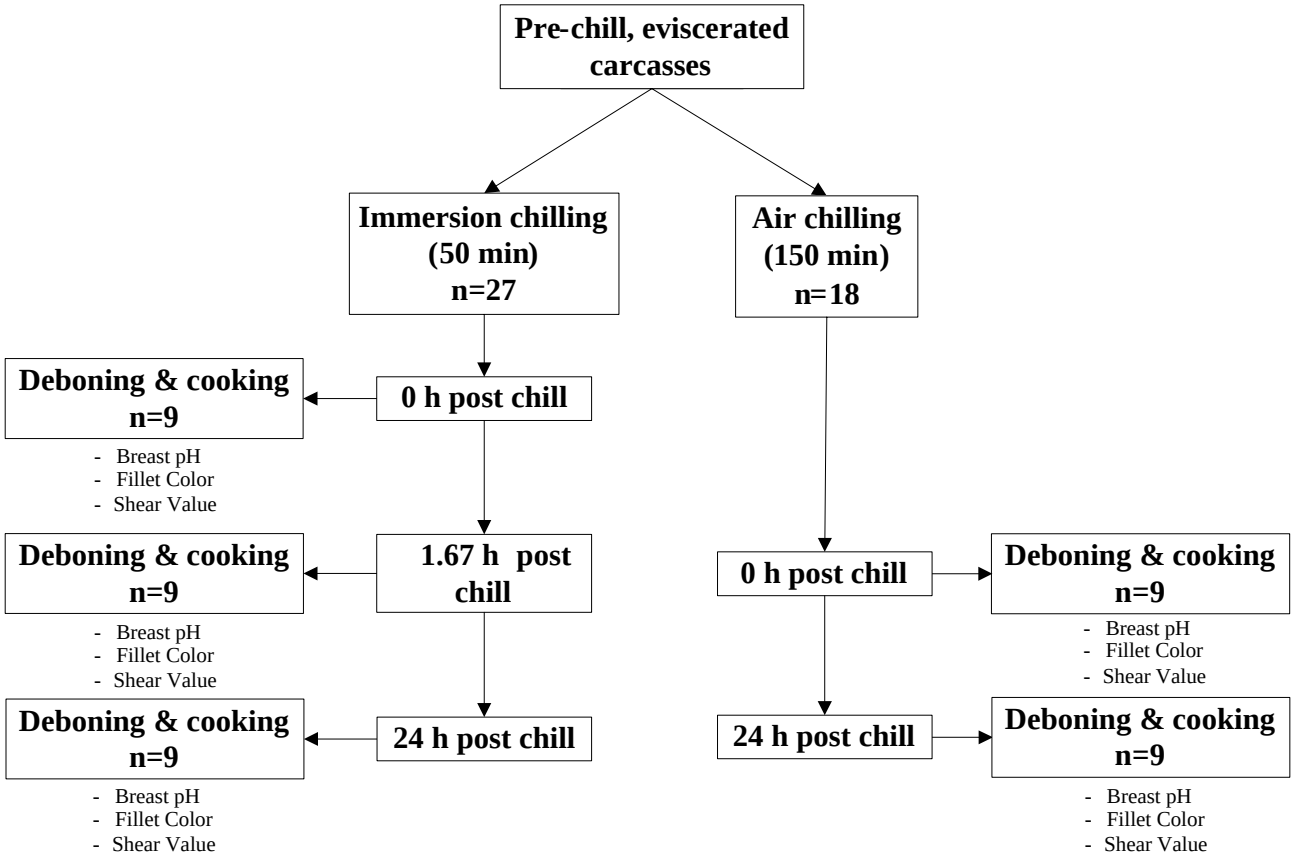


FIGURE 4.2. Distribution of raw breast fillets pH deboned 0h post air chilling or 1.67 post immersion chilling

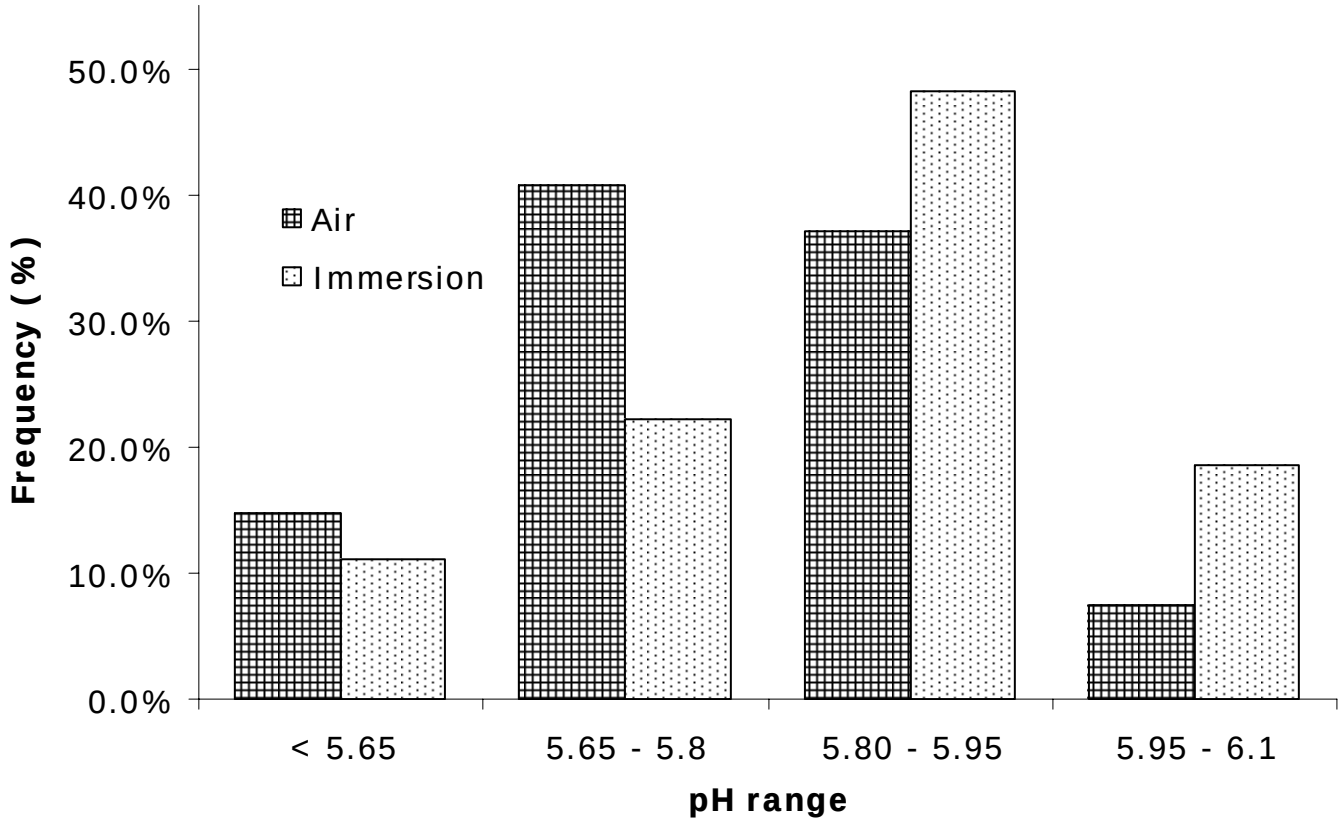
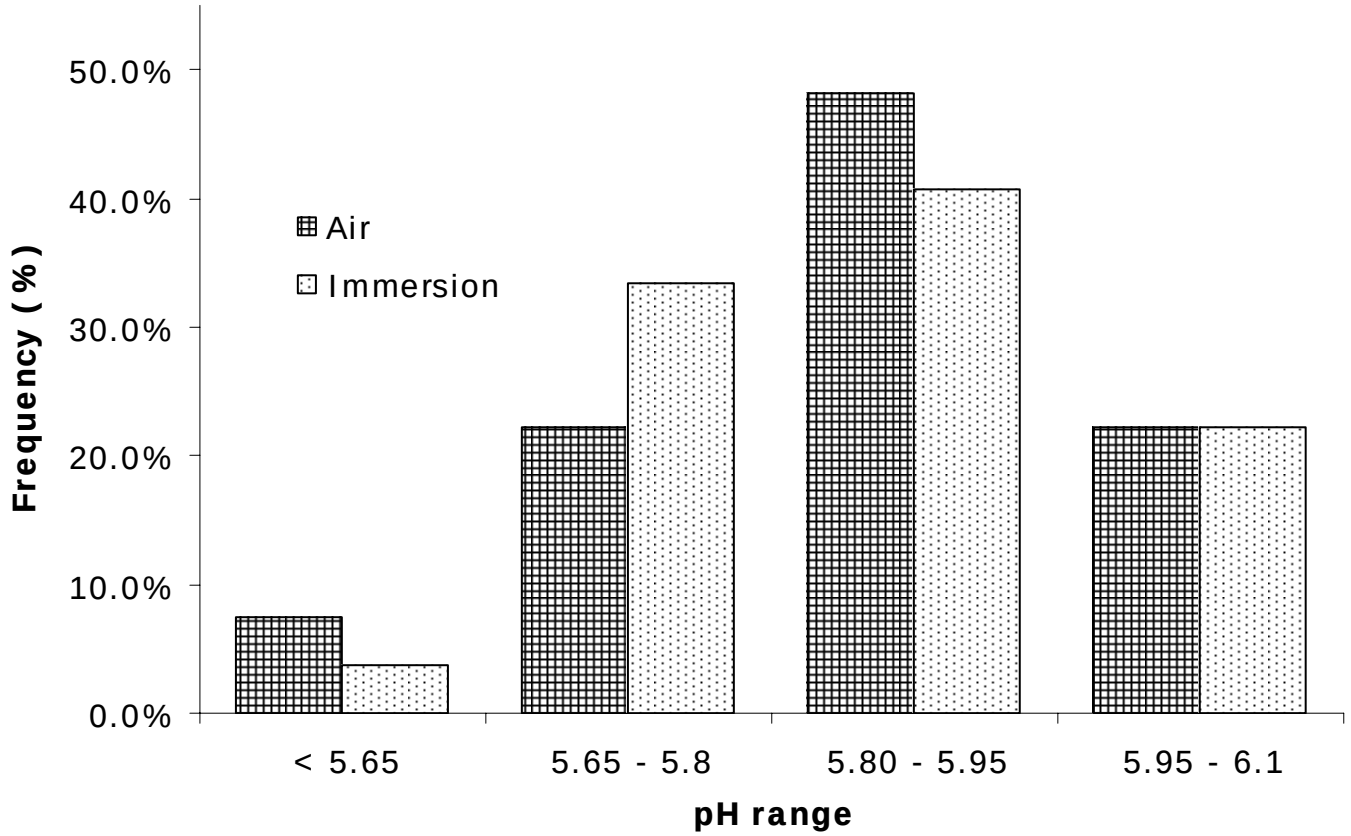


FIGURE 4.3. Distribution of raw breast fillets pH deboned 24 h post-chilling



CHAPTER 5

SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

Air, immersion and evaporative are the three most common methods of chilling poultry carcasses. Overall, it is clear there is a difference in water absorption and final product appearance among chilling methods. But differences related to meat functionality, meat quality, and hygienic operation and cross contamination are not as clear. From the analyses of the present work we conclude:

- Air and immersion chilling are microbiologically equivalent. Bacterial reductions of up to 1 log unit can be obtained for *E. coli*, coliforms, and *Campylobacter* with dry air or immersion chilling. Chilling method had no effect on prevalence of *Campylobacter* and *Salmonella* positive carcasses.

- Chilling method affects carcass appearance and yield. Breast fillet color, pH and texture of carcasses with the same postmortem time were not affected by chilling method. Fillets functionality was improved by air chilling (higher cook yield). The lower cook yield of immersion chilled breast fillets was the result of high moisture absorption during chilling.
- Air chilling appears to have an effect on rigor mortis, but post-chill aging time is always required to maximize the proportion of tender meat.

- Processors selling whole birds and bone-in parts may find it advantageous to continue with immersion chilling, but for deboning and further processing operations, air chilling is a suitable alternative.