Quality and Sensory Characteristics of Selected Post-Rigor, Early Deboned Broiler Breast Meat Tenderized Using Hydrodynamic Shock Waves

K. I. Meek*, J. R. Claus,†[1] S. E. Duncan,† N. G. Marriott,† M. B. Solomon,‡
S. J. Kathman,‖ and M. E. Marini‖

*Kellogg Brown and Root Inc., 605 East 30th Street, Buena Vista, VA 24416; †Department of Food Science and Technology, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0418; ‡USDA Agricultural Research Service, Meat Science Research Laboratory, Beltsville, Maryland 20705-2350; and ‖Department of Statistics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0439

ABSTRACT Our first objective was to determine the effects of explosive amount and distance of the explosive to the meat surface in the Hydrodyne process on broiler breast tenderness. Early deboned (EB) breasts were removed immediately after initial chill (45 min postmortem), stored for 24 h (4 C), and subjected to one of four Hydrodyne treatments (200 g at 20 cm, 350 g at 23 cm, 275 g at 20 cm, or 350 g at 20 cm). Breasts were water-cooked (78 C internal). Hydrodyne treatment (HYD) of 350 g at 20 cm produced the greatest reduction (28.3%) in Warner-Bratzler shear (WBS, 1.9-cm wide strips). This combination was the only treatment to improve tenderness (peak force 4.3 kg) to a level equivalent ($P > 0.05$) to aged controls (CA; peak force 3.1 kg).

The second objective was to determine the quality and sensory characteristics of Hydrodyne-treated (350 g explosive at 20 cm) broiler breasts as compared with CA and EB. The WBS values (1.0-cm wide and thick strips) for CA (1.56 kg) were different from both HYD (3.7 kg) and EB breasts (4.7 kg). The CA resulted in more tender, flavorful, and juicer breasts than EB and HYD. The EB was higher in initial moisture release than HYD.

The EB breasts with tenderness problems can be tenderized by the Hydrodyne process based on WBS results. However, higher levels of explosive may be required to optimize the tenderness improvement of EB breasts that vary significantly in initial tenderness.

(*Key words*: broiler, breasts, early deboning, tenderness, shock waves)

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INTRODUCTION

A major limiting factor in broiler processing is the need to age broiler breasts prior to deboning. Consumers have found early deboned breasts (EB) to be unacceptably tough (Lyon *et al.*, 1985; Lyon and Lyon, 1990a). A delayed boning time of 4 to 7 h postmortem (which alleviates the toughness problem) results in a costly conversion process, as it involves additional handling, extra storage space, added refrigeration, and results in considerable product shrinkage because of purge (Dickens and Lyon, 1995; Lyon *et al.*, 1989). Poultry aging is the term for the mechanical restraint of chilled broiler breast meat on intact carcasses. The bones prevent shortening of the sarcomeres as rigor develops (Papa and Lyon, 1989). Any muscle that is restrained during rigor formation has the tendency to be tender because of less structural integrity resulting from the lack of overlapping thick and thin filaments of the myofibrils (Smith *et al.*, 1991).

Many technologies, including electrical stimulation (Maki and Froning, 1987; Sams *et al.*, 1989), wing restraints or tensioning (Birkhold *et al.*, 1992; Birkhold and Sams, 1993), marination (Young and Lyon, 1997), and a combination of these methods (Sams, 1990; Sams *et al.*, 1991) have provided positive results in improving EB broiler breast tenderness. In addition to decreasing shear values of turkey breasts, electrical stimulation significantly decreased Hunter Lab L values of cooked meat (Maki and Froning, 1987). However, as reviewed by Li *et al.* (1993), research with electrical stimulation of broiler breasts has produced inconsistencies because of different times of electrical stimulation application, aging techniques, electrical parameters such as voltage, frequency and wave cycle, variable tenderness analysis procedures, and biological and physiological variations. Therefore, none of the aforementioned technologies assure broiler breast tenderness.

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[1]To whom correspondence should be addressed: James R. Claus, Meat Science and Muscle Biology Laboratory, University of Wisconsin-Madison, 1805 Linden Drive West, Madison, WI 53706; e-mail: jrclaus@facstaff.wisc.edu.

Abbreviation Key: CA = aged controls; EB = early deboned; HYD = Hydrodyne treatment; WBS = Warner-Bratzler shear.

Ultrasound has been investigated as a method to tenderize meat. Lyng *et al.* (1997) suggested that ultrasonic techniques cause lysosomal rupture as well as myofibrillar protein and connective tissue disruption that result in tenderization of the meat. In a study of low frequency, high intensity ultrasound baths on beefsteaks, Lyng *et al.* (1997) reported that the ultrasound baths were not effective in improving tenderness of intact beef steaks. These results are inconsistent with a study in which high intensity, low frequency (26 kHz) ultrasound was determined to tenderize *semitendinosus* beef muscle when sonicated for 2 and 4 min (Smith *et al.*, 1991).

Hydrostatics is the study of characteristics of liquids at rest or the force that a liquid imposes on a submerged object (Solomon *et al.*, 1997b). MacFarlane (1973) researched the effects of hydrostatic pressure on beef and lamb. An improvement in tenderness was determined when the meat was treated with hydrostatic pressure of 1.05×10^7 kg/m^2 at 30 to 35 C for 2 min. Kennick *et al.* (1980) confirmed the results of the previous study and determined that hydrostatic pressure accelerated meat aging and improved tenderness. Water-holding capacity was decreased due to cellular disruption in pressurized samples (Kennick *et al.*, 1980). Further sensory studies have not been conducted to determine the consumer response to pressurized meat. Kennick *et al.* (1980) reported obvious visual contraction of treated muscles, and MacFarlane (1973) reported a notable change in firmness of treated raw muscles. This technology lacks extensive development and industrial applications found in other areas.

The Hydrodyne process, redesigned by John Long, (US Patent #5,273,766 and #5,328,403), is a novel technology being developed and tested by the USDA's Agricultural Research Service Meat Science Research Laboratory to tenderize beef, pork, and lamb (Solomon *et al.*, 1996; Solomon *et al.*, 1997a; Solomon *et al.*, 1997b). The Hydrodyne process is the use of a hydrodynamic force of a shock wave on an object in a fluid. The shock wave travels rapidly through the fluid (water) and any objects (in the fluid) that are an acoustical match to water (Kolsky, 1980). Because meat is composed of 75% water (Pearson, 1987), the wave passes through the sample and ruptures proteins during the Hydrodyne treatment. The sarcomeres are ruptured indiscriminately through the myofibrillar proteins, z disks, and surrounding structures (Zuckerman and Solomon, 1998; Solomon *et al.*, 1997a). The explosive used to create a shock wave is a combination of nitromethane (liquid) and ammonium nitrate (solid). These components are not explosive until combined (Solomon *et al.*, 1997b). The amount of explosive and the distance from the explosive to the surface of the packaged meat product determine the amount of force imposed on the meat (personal communication, M. Solomon, 1997).

A three-part study conducted by Solomon *et al.* (1997b) analyzed the effectiveness of the Hydrodyne process on fresh, frozen, and hot-boned beef muscles. These studies were conducted in a small-scale Hydrodyne unit consisting of a plastic container (208-L capacity and 51-cm diameter) fitted with a 2-cm thick steel plate (Solomon *et al.*, 1997b). The container was situated below ground level and filled with water. The first part examined different amounts of explosive (50, 75, and 100 g) suspended at 30.5 cm from the meat surface and the effects of multiple Hydrodyne treatments. Fresh and frozen longissimus muscle (LM) steaks were treated. Solomon *et al.* (1997b) reported a reduction in Warner-Bratzler shear (WBS) force of 49 to 72% for the fresh cooked LM steaks. The meat treated with two concurrent blasts (Hydrodyne treatment) resulted in the largest shear-force improvement (72%). The second study consisted of fresh beef *biceps femoris* treated with the Hydrodyne process (50, 75, and 100 g of explosive). Based on shear force data, these muscles were considered initially tender; however, the Hydrodyne process still resulted in a 19 to 30% reduction in shear values. No differences in raw appearance or color were noted in the muscles posttreatment. In the third study, selected loin and round muscles were hot-boned from 2-year-old Holstein cows and were stored (1 d at 4 C), subsequently frozen (–34 C), and then thawed before Hydrodyne treatment. The LM tenderness was improved by 66%, and the round muscles were improved as much as 53 to 59% using the Hydrodyne process (100 g of explosive) compared with untreated muscles. The authors suggested that the high shear values in the nonhydrodyne-treated muscles were due to cold shortening; therefore, the Hydrodyne treatment effectively tenderized cold-shortened meat (Solomon *et al.*, 1997b).

Currently, no known published material exists on utilizing the Hydrodyne technology to tenderize EB broiler breasts. The objectives of this study were first to determine the effect of different combinations of explosive amount and distance of explosive to meat surface for tenderizing EB broiler breasts using the Hydrodyne process. From the results of the first objective, the most effective Hydrodyne treatment was selected for determining the sensory and quality characteristics of Hydrodyne-treated EB broiler breast meat.

MATERIALS AND METHODS

Sample Preparation and Treatment

Fresh boneless, skinless chicken breasts (*Pectoralis major*) were obtained during 2 different wk (for each objective) from a Virginia processor and were stored overnight at 4 C until treatment. The samples were treated within 1 d postmortem. The breasts included control aged breasts (CA; stored on ice at least 6 h prior to deboning), EB breasts (deboned immediately after the initial chill time during processing; approximately 45 min postmortem), and Hydrodyne treated (HYD) EB breasts. The EB and HYD were obtained from the same carcass. For each breast carcass, one breast was assigned to the EB treatment, and the other breast was assigned to a specific Hydrodyne treatment. The CA breasts were

obtained from different carcasses. Each breast was labeled with a brine tag inserted through the thin, posterior end of the breast with a tagging gun.

For Objective 1, four treatments were tested using specific explosive levels and distance of explosive to meat surface combinations including: 200 g at 20 cm, 350 g at 23 cm, 275 g at 20 cm, and 350 g at 20 cm. Based on explosive modeling curves developed by Hydrodyne Incorporated (San Juan, Puerto Rico), these combinations produced pressure fronts of 142 MPa (20,600 psi), 159 MPa (23,000 psi), 163 MPa (23,600 psi), and 177 MPa (25,700 psi), respectively. The initial explosive level and distance combinations used in this study were determined based on a nonreplicated preliminary study (unpublished data). The explosive level of 200 g at 20 cm and 26.4 cm was tested to determine effectiveness of the Hydrodyne process on EB broiler breasts. The 200 g at 20 cm produced a greater improvement in tenderness as compared with the 200 g of explosive at 26.4 cm. Breasts (five per bag) designated for Hydrodyne treatments were vacuum-packaged[2] (seal settings 6.0, full vacuum) in sized and sealed 35- × 37.5-cm bone-guard bags.[3] Breasts were treated for each pressure front level, and each treatment was replicated three times. The packaged breasts were positioned in the bottom center of the stainless steel 1,060-L capacity Hydrodyne tank with the skinless skin side of the breasts closest to the explosive. The Hydrodyne tank was supported by eight rubber gasket-lined mounting braces. A certified explosive expert performed the handling and detonation of the explosive. The Hydrodyne process was conducted in a commercial pilot plant facility.[4]

For Objective 2, one breast (alternating left and right) from each EB was assigned to the EB treatment, and the opposite breast was assigned to a Hydrodyne treatment. A separate set of aged broiler breasts was evaluated as CA samples. The HYD samples were treated with the most effective explosive level and distance from explosive to meat surface combination of 350 g at 20 cm (25,700 psi) and compared with CA and EB breasts. Approximately 10 breasts per bag were vacuum-packaged. Replications 1 and 2 were vacuum-packaged[2] (seal settings 5.0, full vacuum) in 48-Ga PET adhesive laminated multilayer sealant LLDPE.[5] Replications 3 and 4 were vacuum-packaged in coextruded film bags with an EVOH barrier, LLDPE sealant, and nylon structural layers.[6] The different bags were used because no single bag type had been previously established to prevent bag failure when used in the Hydrodyne process. Based on unpublished data, differences in bags have not had any significant effect on the efficacy of the Hydrodyne process (personal communication, Morse Solomon, 1997). The packaged products were positioned in same manner in the Hydrodyne tank as in Objective 1.

Sample Cookery

The breasts were individually vacuum-packaged[5] after the Hydrodyne process and were stored (4 C) until cooked at 3 d postmortem using a sous-vide method modified from Lyon and Lyon (1990b). The breasts were cooked fresh instead of from the frozen state and were cooked to an internal temperature of 78 C in an in-house manufactured circulating water bath preheated and maintained at 78 C. Several representative samples were placed in different locations in the water bath with Type T thermocouples[7] inserted into the thickest part of the breasts to monitor core temperature. Temperature data were collected using an automatic data recorder.[8] Another deviation from the procedure of Lyon and Lyon (1990b) was that once the breasts reached an internal temperature of 78 C, the samples were held at that temperature for 10 min. The breasts were removed from the bath and immediately cooled in ice slush for 10 min and then stored at 4 C until further analysis.

Shear Force Measurements

Tenderness was assessed the same day (within 5 h) that the breasts were cooked. For Objective 1, a modified objective texture method (Lyon and Lyon, 1990b) was used. The strips were modified by using a 3.0-cm strip length cut medially and adjacent to one another, rather than cut in half lengthwise. Five breasts, equilibrated to room temperature from each treatment, were used for shear force determinations. Two adjacent 1.9-cm wide strips were cut from the medial area of the cooked breast parallel to the muscle fibers. Each strip was sheared two to three times, and an average was calculated for the breast. Samples were sheared perpendicular to the muscle fibers using a WBS attachment mounted on an Instron.[9] A 50-kg load transducer and a crosshead speed of 200 mm/min were used.

For Objective 2, nine breasts, equilibrated to room temperature from each treatment, were used for shear force determinations. Two adjacent 1.0-cm strips (width and height) were cut from the medial area of the cooked breast parallel to the muscle fibers. The first cut of the breast was made 2 cm from the thick anterior end of the breast. A strip was then cut parallel to the muscle fibers. Once muscle orientation was determined for that strip, the strip was trimmed to 1.0 cm. This process was repeated for each strip. All strips were cut from the center of each breast and were trimmed to a length of 3.0 cm. The first, second, and third strips from the anterior to posterior end of each breast were allotted to sensory, WBS, and Lee-Kramer shear, respectively. This sampling

[2]Model LV10 Hollymatic with dual seam.
[3]B-6250, bone-guard, Cryovac North America, Division of WR Grace & Co., Duncan, SC 29334.
[4]Dynawave Inc., Buena Vista, Virginia 24416.
[5]H6230B, Cryovac North America, Division of WR Grace & Co., Duncan, SC 29334.
[6]9450-AA, Curlon grade, Curwood Inc., Oshkosh, WI 54901.
[7]Omega Engineering, Inc., Stamford, CT 06907.
[8]Model 5100, Datalogger, Electronic Controls Design, Inc., Milwaukie, OR 97222.
[9]Model 1011, Instron Corp., Canton, MS 39046.

strip method was determined in preliminary studies to allow for the control of fiber direction. One strip was sheared perpendicular to the muscle fibers using a WBS attachment mounted on the Instron. A 50-kg load transducer and a crosshead speed of 200 mm/min were used. The strip was sheared three times, and an average was calculated. The second 1.0-cm strip was weighed and sheared using a Lee-Kramer shear attachment mounted on the Instron. To determine the total energy (kg × mm) per gram, a 500-kg load transducer and a crosshead speed of 200 mm/min were used.

Sensory Evaluation

Nine panelists consisting of employees at Virginia Tech evaluated CA, EB, and HYD-treated samples. The panelists were trained in four sessions that lasted approximately 1 h each. The panelists evaluated the tenderness, moisture release (initial and sustained), and chicken flavor of the samples. The tenderness characteristic was based on myofibillar tenderness and was measured within the first five chews. Myofibrillar tenderness referred to the lean muscle fibers rather than connective tissue (e.g., epimysium and tendons). Tenderness was defined as the ease of fragmentation or the ability for the teeth to cut across the meat fibers. By altering cooking techniques for aged broiler breasts, the reference standards for tenderness were developed. Breast samples were sous vide cooked to three internal temperatures (85 C, 78 C, and 74 C) to provide a range of tenderness (not tender to very tender). The reference standards for moisture release (initial and sustained) consisted of a modified wetness scale (Meilgaard *et al.*, 1991). A carrot (low initial, low sustained), apple (high initial, low sustained), and ham (moderate initial, high sustained) were used for the initial training phases of the panelists for the moisture release characteristic. Initial moisture release was measured within the first five chews. Sustained moisture release was measured as the amount of moisture released as the sample was masticated until it was suitable for swallowing. In the latter stages of training, moisture release was evaluated on sous vide breast samples cooked to three internal temperatures (85 C, 78 C, and 74 C). Chicken flavor was defined as the amount of chicken flavor in a sample. By boiling chicken thighs in water (237 ml water per chicken thigh), the reference standards for flavor were created. The thighs were boiled for 3 h and then removed. The stock was chilled and skimmed of excess fat. This stock was used for the high end (strong chicken flavor) of the line scale for flavor. The bones from the boiled thighs were removed and boiled (3 h) in 237 ml water per thigh bone, chilled, and skimmed of excess fat to create the anchor definition of slight at the low end of the scale.

Nine breasts cooked by the aforementioned sous vide method were evaluated by the experienced sensory panel within 3 h of cooking. The third 1.0-cm strip, taken from each breast with the procedure outlined in shear evaluations, was used for sensory evaluation. All strips were trimmed to a length of 3.0-cm, stored individually in capped plastic containers (4 C), and then served at room temperature. Nine panelists evaluated 1.0-cm strip samples for tenderness (0 = not; 15 = very), initial moisture release (0 = none; 15 = extreme), sustained moisture release (0 = not; 15 = very), and chicken flavor (0 = slight; 15 = strong) on unstructured line scales (15.0 cm). Panelists were instructed to cleanse their palates with water between each sample and to wait 60 s before tasting the next product. The panelists conducted the sensory evaluation in a sensory panel booth under red lighting to eliminate any color differences. The strip samples were randomly presented in capped containers coded with randomly selected three-digit codes. Each panelist evaluated the samples independently. For each panelist, the EB sample was paired with its corresponding EB Hydrodyne treated breast sample; however, the panelists were not aware of the pairing.

Purge Losses and pH

Two breasts from each treatment were weighed prior to treatment and after 24 h of refrigerated storage. Two CA breasts, EB breasts, and companion HYD breasts were stored in oxygen-permeable PVC wrap and were patted dry before weighing at room temperature. The percentage of weight loss was calculated for storage purge losses using the equation (initial weight – 24 hr weight)/initial weight × 100. The initial pH of the CA and EB breasts was measured using a pH probe[10] inserted into the thick anterior region of the breasts.

Breast Plumpness

The thickness of two breasts per treatment of similar weight was measured every 2 cm of the breast length from the anterior (thick end) to posterior end before and after Hydrodyne treatment. The EB breasts were measured and then treated with the Hydrodyne process. Measurements were taken by piercing the breasts with a metal probe (0.2-cm diameter) in the same locations, prior to and after, Hydrodyne treatment.

Cooking Loss

The cooking loss was determined on all samples cooked for sensory determination. The surface of the raw and cooked samples was patted dry weighed at refrigerated temperature (4 C). Cooking loss values were calculated based on the equation of (raw weight – cooked weight)/raw weight × 100. An average cooking loss was determined for each treatment group (CA, EB, and HYD).

[10]Model IQ200, pH05 stainless steel ISFET probe with a 60° tip, IQ Scientific Instruments, Inc., San Diego, CA 92198.

Instrumental Color

Fresh, untreated breasts destined for the Hydrodyne treatment were analyzed for CIE L*a*b* readings using a chroma meter.[11] The chroma meter was calibrated using a standard calibration plate.[12] Three readings were taken on two breasts per treatment (EB, HYD, and CA) on the lateral (skin side) and medial (bone side) sides of the breasts, before the Hydrodyne treatment and after treatment. Breasts were exposed to air for 30 min prior to color analysis by suspending the breast by the thin, posterior end of the muscle.

Cooked color of two samples from each treatment was analyzed using the chroma meter calibrated against the standard white plate. Three readings were taken on the medial and lateral sides of the breasts, and an average by location was calculated.

Statistical Analysis

Objective 1. Early deboned breasts with mean peak force values less than 3.62 kg and their corresponding treatment breasts were eliminated from the data set. This removal was done because Lyon and Lyon (1990b) reported that breast meat with a peak force of 3.62 kg was determined to be "very tender" in consumer studies.

For both objectives. The peak force shear values were averaged over breast for each treatment, as each breast within a blast represented a subsample. The CA and HYD treatment significance was determined by the ANOVA procedure using the general linear models procedure of SAS (1992). Paired sample *t*-tests (proc univariate) were utilized to evaluate differences between EB-treated and paired, HYD-treated EB samples. The *t*-test was used because a lack of independence between the two samples. Additionally, the significance between CA and EB controls was determined with a two-sample *t*-test (proc ttest) of SAS (1992).

These same statistical procedures were also utilized to determine differences in raw color, cooking loss, cooked color, and purge losses and differences for each characteristic of sensory evaluation. The sensory scores were averaged for each treatment within a replication. The paired EB and HYD samples were evaluated with paired sample *t*-tests (proc univariate) for each of the aforementioned characteristics. The CA and EB controls as well as the CA and HYD samples were compared with two-sample *t*-tests (proc ttest) of SAS (1992) for each characteristic.

Plumpness was analyzed by the paired *t*-test procedure of SAS (1992). This procedure was used because of a lack of independence for each measurement within a breast. Initial pH analysis was determined using a two-sample *t*-test (proc ttest) of SAS (1992).

[11]Model CR-200, Minolta Corporation, Ramsey, NJ 07446.

[12]White plate, No. 20933026; CIE L* 97.91, a*, –0.70, b* +2.44, Minolta Corporation, Ramsey, NJ 07446.

RESULTS AND DISCUSSION

Objective 1: Explosive Amount and Distance Effects

The original data set contained 15 samples for each treatment (three replications) except Treatment 4, which contained 13. The number of breasts varied by treatment because of standardization of the data to eliminate pairs with shear force values <3.62 kg, which would correspond to chicken that was considered very tender (Lyon, and Lyon, 1990b). Sams and Janky (1986) reported that early deboning of broiler breast meat results in unacceptable toughness, and the variability of tenderness of EB samples is increased between carcasses.

The broiler breasts treated with an explosive and distance combination of 350 g at 20 cm (Treatment 4) were more tender ($P < 0.05$) than their paired EB breasts and were also similar ($P > 0.05$) to the aged controls (Table 1). These data indicate that Treatment 4 was the most effective explosive and distance combination of those levels examined. Treatment group 2 was the only other group that produced a lower ($P < 0.05$) shear force using the Hydrodyne treatment compared with the companion nontreated EB breasts. However, this treatment did not improve tenderness to a level equivalent to the aged controls. The mean WBS value of the aged controls was 3.1 kg, which would correspond to a breast rated as tender on the sensory scale developed by Lyon and Lyon (1990b). Mean shear value of Treatment 4 of 4.3 kg corresponded to breasts rated in the slightly to moderately tender category (Lyon and Lyon, 1990b).

The shear sample width (1.9 cm) was controlled for each sample; however the thicknesses of the shear samples were left as the natural breast thicknesses (approximately 1.3 cm to 1.9 cm), which was consistent with Lyon and Lyon (1990b) and Papa and Lyon (1989). Although not determined, if this irregularity in natural breast thickness occurred among the treatment groups, it may, in part, explain some of the differences among EB control groups. In Objective 2, the thickness and the width of the samples were controlled.

A 28.3% improvement in broiler breast tenderness was realized for Treatment 4. In other Hydrodyne studies with hot-boned beef muscles stored for 24 h before Hydrodyne treatment, a 53 to 66% range of tenderness improvement was realized (Solomon *et al.*, 1997b). This percentage range was related to differences in the muscles tested (longissimus, 66%; biceps femoris, 53%). The explosive and distance combinations used in our study produced a pressure front range of 142 MPa (20,600 psi) to 177 MPa (25,700 psi). In the beef study, the pressure fronts were measured in the range of 6.05×10^6 to 7.03×10^6 kg/m^2. The differences between percentage improvement in tenderness of beef *vs* chicken may be related to differences in the physical nature of the meat. In general, beef is a firmer and more rigid muscle than chicken, which is soft and pliable (Judge *et al.*, 1989). Additionally differences between Hydrodyne tenderiza-

TABLE 1. Warner-Bratzler shear peak force values for Hydrodyne-treated, skinless early deboned broiler breasts; companion early deboned (no treatment) breasts; and aged (control) breasts cooked to 78 C

		Peak force (kg)		
Group[1]	n	Nonhydrodyned	Hydrodyned	SD[2]
Differences in mean shear values for companion early deboned Hydrodyne-treated and nontreated breasts				
Treatment 1	10	6.2^{abx}	5.4^{x}	1.8
Treatment 2	10	7.5^{ax}	5.6^{y}	2.5
Treatment 3	8	5.4^{bx}	4.7^{x}	1.1
Treatment 4	11	6.0^{bx}	4.3^{y}	1.2
		(MSE 1.84)		
Aged control *vs.* Hydrodyne breasts				
Aged	15	3.1^{b} ± (0.9)[3]		
Treatment 1	10	5.4^{a} ± (2.0)		
Treatment 2	10	5.6^{a} ± (2.0)		
Treatment 3	8	4.7^{a} ± (1.7)		
Treatment 4	11	4.3^{ab} ± (1.9)		
		(MSE 2.34)		

[a,b]Means within a column and part with unlike letters are different at $P < 0.05$ by Duncan's new multiple range test.

[x,y]Means within a row with unlike letters are different at $P < 0.05$. Due to a lack of independence within a chicken breast, a paired *t*-test was used to compare the nonhydrodyned vs the hydrodyned treatments.

[1]Group: Aged = breasts removed 6 h postmortem; Treatment groups 1 through 4 represent different Hydrodyne treatments, listed as grams of explosive and distance of explosive to meat surface; 1 = 200 g at 20 cm (20,600 psi); 2 = 350 g at 23 cm (23,000 psi); 3 = 275 g at 20 cm (23,600 psi); and 4 = 350 g at 20 cm (25,700 psi).

[2]Standard deviation for paired differences between companion breasts (Hydrodyne minus non-hydrodyne).

[3]SD.

tion may be due to fiber orientation in beef steaks *vs* chicken breast fillets. As shock waves change the microstructure of solids, and, subsequently, the mechanical properties of the solids subjected to shock loads, an increase in hardness may occur (Batsanov, 1994). This hardening effect occurs in metals such as steel alloys. The hardness developed can change as very high pressures decrease metal hardness due to residual heating (Batsanov, 1994). The shock wave generated during the Hydrodyne process may compress and compact the chicken fibers, causing hardening and resulting in a less tender product. No known literature exists on the effects of shock waves on biological tissues in relation to food quality characteristics. The texture of the chicken breasts did not appear to be over-tenderized (visually or physically mushy).

Objective 2: Sensory and Quality Characteristics

There was a 19.1% improvement in tenderness of the HYD over the EB for the WBS measurements and a 9.1% improvement in Lee-Kramer (LK) total energy measurements (Table 2). However, the Hydrodyne treatment did not produce a product as tender as did the CA, as determined by WBS and LK shear measurements. The magnitude of the improvement in tenderness (19.1%) was less than that determined in Objective 1 (28.3%). The EB breasts were not standardized for initial tenderness as done in Objective 1 because the sampling method was changed from Objective 1 to Objective 2. In Objective 1, the samples were obtained using the same method as Lyon and Lyon (1990b); therefore, the data set could be standardized.

The sample strips for our study (Objective 2) were cut starting from the thick, anterior end of the breasts. Then the strip was trimmed of the outer edges until a middle 1.0 cm wide and thick strip (parallel to muscle fibers) was obtained. Only the widths (1.9 cm) of the strips were controlled in Objective 1. The three strips from Objective 1 resulted in a greater area of the breast required for sampling. As these strips were larger, the thinner, poste-

TABLE 2. Mean Warner-Bratzler (WBS) and Lee-Kramer (LK) shear force values for Hydrodyne treated (350 g explosive at 20 cm) skinless early deboned broiler breasts, companion early deboned (no treatment) breasts, and aged (control) breasts

Treatment	n	WBS Peak force (kg)	n	LK Total energy (kg × mm/g)
Aged	36	1.6^{b} ± (0.3)	36	6.0^{b} ± (1.8)
Early deboned	36	4.7^{a} ± (2.6)	33	12.1^{a} ± (3.8)
Early deboned	36	4.7^{a}	27	12.1^{a}
Hydrodyne	36	3.8^{b}	27	11.0^{b}
SD[1]		(2.1)		(2.9)
Aged	36	1.6^{b} ± (0.3)	36	6.0^{b} ± (1.8)
Hydrodyne	36	3.8^{a} ± (1.8)	29	11.0^{a} ± (4.0)

[a,b]Means ± (SD) within a column and treatment comparison with unlike letters are different at $P < 0.05$ by two-sample *t*-tests with degrees of freedom adjusted using a Satterthwaite correction, because variances were unequal (therefore no pooled mean square error is reported).

[1]SD = Standard deviation for paired differences between companion breasts (Hydrodyne-early deboned).

TABLE 3. Mean sensory values for flavor (FLV), initial moisture release (IMR), sustained moisture release (SMR), and tenderness (TEND) of Hydrodyne-treated, skinless, early deboned broiler breasts; companion early deboned (no treatment) breasts; and aged (control) breasts evaluated by a trained sensory panel

	Sensory Characteristic[2]			
Treatment	FLV	IMR	SMR	TEND
Aged[1]	8.6[a]	8.0[a]	9.2[a]	10.9[a]
Early deboned (control)[1]	7.1[b]	7.4[a]	8.1[a]	6.0[b]
MSE[3]	(7.4)	(7.3)	(6.9)	(9.3)
Early deboned[4]	7.1[a]	7.4[a]	8.1[a]	6.0[a]
Hydrodyne[4]	6.3[a]	5.8[b]	6.9[a]	6.7[a]
SD[5]	(3.6)	(3.0)	(3.6)	(4.2)
Aged[1]	8.6[a]	8.0[a]	9.2[a]	10.9[a]
Hydrodyne[1]	6.3[b]	5.8[b]	6.9[b]	6.7[b]
MSE[3]	(6.3)	(7.6)	(8.8)	(8.6)

[ab]Means within a column and treatment comparison with unlike letters are different at $P < 0.05$.

[1]Two sample *t*-tests were used to analyze differences with equal variances.

[2]Sensory characteristics were rated on a 15-cm line scale: FLV is the intensity of chicken flavor where 0 = slight and 15 = strong; IMR is the initial moisture release evaluated in the first five chews where 0 = none and 15 = extreme; SMR is the amount of moisture released as the sample was masticated until it was suitable for swallowing where 0 = not and 15 = very; and TEND is the myofibrillar tenderness measured in the first five chews where 0 = not to 15 = very tender.

[3]Mean square error.

[4]Paired differences between companion breasts were analyzed with paired *t*-tests.

[5]SD = Standard deviation for paired differences between companion breasts (Hydrodyne-early deboned).

rior end of the breast was included in some samples depending on breast size. The strips in Objective 2 were more controlled and were obtained from the same thick, anterior end of the breast. These differences in strip sampling may provide evidence for differences in CA shear values in Objective 1 (3.1 kg) and Objective 2 (1.6 kg). The LK values reported for CA in our study (12.1) are slightly higher than values reported by Bilgili *et al.* (1989) of 10.1 and 11.1 kg/g for aging (4 h) temperatures of 0 C and 14 C, respectively. Additionally the sample size in our study (1.0 × 1.0 × 3.0 cm) was larger than the Bilgili *et al.* (1989) study samples (0.2 × 0.4 × 0.3 cm).

Sensory Evaluation. The CA was more ($P < 0.05$) flavorful and tender than EB (Table 3), which agrees with our instrumental tenderness results. No differences ($P > 0.05$) in moisture release between CA and EB were noted, which agrees with Lyon and Lyon (1996). Lyon and Lyon (1997) reported that juiciness was not correlated with instrumental tenderness. It was expected that a less intense flavor of the EB breasts would correspond to increased moisture release because EB breasts have more contracted sarcomeres (Dunn *et al.*, 1993) and decreased spatial ability to bind water (Judge *et al.*, 1989). The instrumental differences in tenderness were not at a perceivable difference for the experienced panel in this study.

The initial moisture release for the HYD breasts was lower ($P < 0.05$) than the EB. Therefore the HYD samples were juicier within the first five chews of the sample. No other differences were noted between HYD and EB (Table 3). However, the WBS and LK tenderness measurements indicated that the HYD was more ($P < 0.05$) tender than the EB breasts. The experienced panel did not perceive this difference (Table 3).

The HYD had a less intense ($P < 0.05$) flavor, lower ($P < 0.05$) initial and sustained moisture release and was less ($P < 0.05$) tender than CA (Table 3). Meaty flavor associated components are contained in the water-soluble fractions of muscle tissue (Judge *et al.*, 1989). HYD had the highest cooking loss of all treatments, and this extra moisture loss may contribute to lower flavor response in HYD breasts.

Plumpness. Although not statistically analyzed, breast plumpness decreased from anterior to posterior ends regardless of treatment (Table 4). The overall mean plumpness value was not determined, because plumpness was determined at specific incremental distances along the breast. Hydrodyne treatment decreased ($P < 0.05$) breast plumpness at sample locations of 2, 4, 6, and 8 cm compared with the companion EB breasts (Table 4). Beyond the 8-cm measurement, EB and HYD did not differ in plumpness.

pH and Purge Loss. The initial pH of EB breasts (5.71) was lower ($P < 0.05$) than the CA (5.86), which agrees with Dunn *et al.* (1993). In contrast, Sams *et al.* (1990) reported a chill-boned breast (deboned 1 h postmortem) final pH of 5.86 that was similar to the age-boned breast final pH of 5.80. The aged controls in our study were aged for 6 h prior to deboning, whereas the Sams *et al.* (1990) age-boned breasts remained intact for 24 h. Conversely, Dunn *et al.* (1995) reported pH values of 5.93 for aged controls (24 h). pH for Hydrodyne treated breasts was not determined.

Purge loss was not affected by treatment (Table 5). In contrast, Solomon et al. (1996) reported that Hydrodyne-treated pork longissimus muscles had a 14% decrease in purge loss compared to non-Hydrodyne-treated samples. Our study agrees with Froning and Ujttenboogaart (1988), who reported that expressible moisture was not affected by deboning time when broilers were held at 15 C.

Cooking Loss. There were no differences in cooking loss between CA and EB (Table 5). The HYD had a higher cooking loss than the EB samples (Table 5). The higher cooking loss for HYD samples would support the result of lower initial moisture release determined by sensory testing. The CA breasts were not different ($P > 0.05$) in cooking loss than HYD (Table 5). Bilgili *et al.* (1989) determined that postmortem aging temperatures of 28 or 41 C increased cooking losses, and an aging temperature of 0 C decreased cooking losses compared with aging at 14 C.

CIE L*a*b* Color. The raw CA breasts were more red ($P < 0.05$) than the EB breasts (Table 6). The HYD breasts were darker ($P < 0.05$) on the skin side than EB breasts.

TABLE 4. Plumpness for skinless early deboned broiler breasts and companion Hydrodyne-treated (350 g explosive at 20 cm) breasts

	Location[1]					
Treatment[2]	2 cm	4 cm	6 cm	8 cm	10 cm	12 cm
Eary deboned	1.9[a]	1.7[a]	1.4[a]	1.2[a]	0.8[a]	0.6[a]
Hydrodyne	1.7[b]	1.5[b]	1.3[a]	1.0[b]	0.8[a]	0.6[a]
SD[3]	(0.2)	(0.2)	(0.2)	(0.2)	(0.3)	(0.3)

[ab]Means within a column with unlike letters are different at $P < 0.05$ by paired *t*-tests.

[1]Location of plumpness measurement taken every 2 cm of the breast length beginning at the thick, anterior end (2 cm) and ending at the thin, posterior end (12 cm) of the breast.

[2]Early deboned breasts removed from the carcasses immediately after the initial chill (45 minutes postmortem) and stored for 24 h. Early deboned breasts (n = 8) were measured using a metal probe (0.2-cm diameter) by piercing the breast at each location. These breasts were then treated with the Hydrodyne process and remeasured at the exact locations as prior to treatment.

[3]SD = Standard deviation for paired differences between Hydrodyne and early deboned breasts.

No other color differences were determined between HYD and EB (Table 6). The HYD resulted in breasts that were less ($P < 0.05$) red than CA regardless of location (Table 6). No other color differences were noted between CA and HYD.

In Replication 1, an undetermined number of the bags failed during the Hydrodyne treatment. This failure may have allowed for the possibility of contaminants coming in contact with some of the breasts, resulting in a darker color. The explosive used to create the shock wave was a combination of nitromethane (liquid) and ammonium nitrate (solid). A potential byproduct produced during treatment is nitric oxide. In meat, nitric oxide acts as a ligand to bind to the heme iron of metmyoglobin to produce nitric oxide metmyoglobin, which is a brown pigment (Judge *et al.*, 1989). When this pigment is reduced to nitric oxide myoglobin, it forms a red pigment (Fox, 1987; Judge *et al.*, 1989). Therefore, if nitric oxide reacted with the heme iron in the Hydrodyne-treated broiler breasts, oxidation to a brown color would have resulted in less red, darker breasts as compared with CA.

The raw color of the bone side of the CA breast was characterized as more ($P < 0.05$; Table 7) red (higher a* value) and more ($P < 0.05$) yellow (higher b* value) than the skin side of the breast. Conversely, the EB was lighter ($P < 0.05$) on the inside of the breast. Similarly, both the EB and HYD were more ($P < 0.05$) yellow (higher b*

TABLE 5. Purge and cooking losses for Hydrodyne-treated (350 g explosive at 20 cm), skinless early deboned broiler breasts; companion early deboned (no treatment) breasts; and aged (control) breasts after 24 h of storage at 4 C

Treatment	n	Purge Loss (%)	Cooking Loss (%)
Aged[1]	8	0.86[a]	20.5[a]
Early deboned[1]	8	0.84[a]	20.1[a]
MSE[2]		(0.4)	(7.3)
Early deboned[3]	8	0.84[a]	20.1[b]
Hydrodyne[3]	8	0.55[a]	22.2[a]
SD[4]		(0.8)	(3.9)
Aged[1]	8	0.86[a]	20.5[a]
Hydrodyne[1]	8	0.55[a]	22.2[a]
MSE[2]		(0.7)	(13.1)

[a,b]Means within a column and treatment comparison with unlike letters are different at $P < 0.05$.

[1]Two sample *t*-tests were used to analyze differences with equal variances.

[2]Mean square error.

[3]Paired differences between companion breasts were analyzed with paired *t*-tests.

[4]SD = Standard deviation for paired differences between companion breasts (Hydrodyne-early deboned).

TABLE 6. Raw color (CIE L*a*b* values) for Hydrodyne-treated (350 g explosive at 20 cm), skinless, early deboned broiler breasts; companion early deboned (no treatment) breasts; and aged (control) breasts for skin and bone side of the breasts

		CIE Values		
Treatment and Location	n	L*	a*	b*
Skin side				
Aged[1]	8	56.94[a]	2.54[a]	1.28[a]
Early deboned[1]	8	58.26[a]	1.38[b]	1.72[a]
MSE[2]		(10.0)	(0.7)	(3.2)
Bone side				
Aged[1]	8	55.98[a]	3.30[a]	3.26[a]
Early deboned[1]	8	54.91[a]	2.78[a]	4.07[a]
MSE[2]		(9.0)	(1.5)	(2.1)
Skin side				
Early deboned[3]	8	58.26[a]	1.38[a]	1.72[a]
Hydrodyne[3]	8	56.34[b]	1.30[a]	1.10[a]
SD[4]		(2.3)	(0.5)	(1.2)
Bone side				
Early deboned[3]	8	54.91[a]	2.78[a]	4.07[a]
Hydrodyne[3]	8	55.58[a]	1.76[a]	3.16[a]
SD[4]		(3.0)	(1.8)	(1.2)
Skin side				
Aged[1]	8	56.94[a]	2.54[a]	1.28[a]
Hydrodyne[1]	8	56.34[a]	1.30[b]	1.10[a]
MSE[2]		(12.0)	(0.4)	(5.0)
Bone side				
Aged[1]	8	55.98[a]	3.30[a]	3.26[a]
Hydrodyne[1]	8	55.58[a]	1.76[b]	3.16[a]
MSE[2]		(9.3)	(0.4)	(3.1)

[a,b]Means within a column and location with unlike letters are different at $P < 0.05$.

[1]Two sample *t*-tests were used to analyze differences with equal variances.

[2]Mean square error.

[3]Paired differences between companion breasts analyzed with paired *t*-tests.

[4]SD = Standard deviation for paired differences between companion breasts (Hydrodyne-early deboned).

TABLE 7. Raw color (CIE L*a*b* values) for the skin and bone sides of Hydrodyne-treated (350 g explosive at 20 cm), skinless, early deboned broiler breasts; companion early deboned (no treatment) breasts; and aged (control) breasts

		CIE Values		
	n	L*	a*	b*
Aged controls				
Skin side	8	56.94[a]	2.54[b]	1.28[b]
Bone side	8	55.98[a]	3.30[a]	3.26[a]
SD[1]		(2.8)	(0.6)	(1.3)
Early deboned				
Skin side	8	58.26[a]	1.38[a]	1.72[b]
Bone side	8	54.91[b]	2.78[a]	4.07[a]
SD[1]		(3.7)	(2.1)	(1.3)
Hydrodyne				
Skin side	8	56.34[a]	1.30[b]	1.10[b]
Bone side	8	55.58[a]	1.76[a]	3.16[a]
SD[1]		(2.4)	(0.3)	(1.2)

[a,b]Means within a column and treatment with unlike letters are different at $P < 0.05$ by paired *t*-tests.

[1]SD = Standard deviation for paired differences between skin and bone sides of the breast.

TABLE 8. Cooked color (CIE L*a*b* values) differences for Hydrodyne-treated (350 g explosive at 20 cm), skinless, early deboned broiler breasts; companion early deboned (no treatment) breasts; and aged (control) breasts for skin and bone sides of the breasts

Treatment and Location	n	CIE Values L*	a*	b*
Skin side				
Aged[1]	8	84.14[a]	2.30[a]	9.58[a]
Early deboned[1]	8	84.55[a]	2.42[a]	9.84[a]
MSE[2]		(5.3)	(0.4)	(0.9)
Bone side				
Aged[1]	8	83.58[a]	2.95[a]	10.40[a]
Early deboned[1]	8	82.62[a]	3.43[a]	10.82[a]
MSE[2]		(6.5)	(0.8)	(0.8)
Skin side				
Early deboned[3]	8	84.55[a]	2.42[a]	9.84[a]
Hydrodyne[3]	8	84.04[b]	2.84[a]	9.89[a]
SD[4]		(2.3)	(0.5)	(1.2)
Bone side				
Early deboned[3]	8	82.62[a]	3.43[a]	10.82[a]
Hydrodyne[3]	8	81.29[a]	3.51[a]	10.31[a]
SD[4]		(3.0)	(1.8)	(1.2)
Skin side				
Aged[1]	8	84.14[a]	2.30[a]	9.58[a]
Hydrodyne[1]	8	84.04[b]	2.84[a]	9.89[a]
MSE[2]		(4.2)	(0.5)	(1.2)
Bone side				
Aged	8	83.58[a]	2.95[a]	10.40[a]
Hydrodyne	8	81.29[a]	3.51[a]	10.31[a]
MSE[2]		(5.0)	(0.3)	(0.9)

[a,b]Means within a column and location with unlike letters are different at $P < 0.05$.

[1]Two sample *t*-tests were used to analyze differences with equal variances.

[2]Mean square error.

[3]Paired differences between companion breasts analyzed with paired *t*-tests.

[4]SD = Standard deviation for paired differences between companion breasts (Hydrodyne-early deboned).

TABLE 9. Cooked color (CIE L*a*b* values) of the skin and bone side of Hydrodyne-treated (350 g explosive at 20 cm), skinless, early deboned broiler breasts; companion early deboned (no treatment) breasts; and aged (control) breasts sous vide cooked to an internal temperature of 78 C

		CIE Values		
	n	L*	a*	b*
Aged Controls				
Skin side	8	84.14[a]	2.30[b]	9.58[b]
Bone side	8	83.58[a]	2.95[a]	10.40[a]
SD[1]		(2.1)	(0.6)	(0.6)
Early Deboned				
Skin side	8	84.55[a]	2.42[b]	9.84[a]
Bone side	8	82.62[a]	3.43[a]	10.82[a]
SD[1]		(2.4)	(0.5)	(1.5)
Hydrodyne				
Skin side	8	84.04[a]	2.84[b]	9.84[a]
Bone side	8	81.29[b]	3.51[a]	10.31[a]
SD[1]		(2.1)	(0.5)	(1.1)

[a,b]Means within a column and treatment with unlike letters are different at $P < 0.05$ by paired t-tests.

[1]SD = Standard deviation for paired differences between skin and bone sides of the breast.

value) on the bone side of the breast compared with the skin side. Additionally, the HYD sample color followed the same trend as the CA such that the samples were also more ($P < 0.05$) red on the bone side of the breast.

No differences in cooked color of the CA and EB were noted for all characteristics (Table 8). The skin side of the HYD breasts were darker ($P < 0.05$) than the EB breasts (Table 8), which was consistent with the raw color of the breasts. The skin sides of HYD breasts were darker ($P < 0.05$) in cooked color than the CA breasts (Table 8), which was not found in the raw breasts. Despite a difference in redness of the raw breasts between HYD and CA, this difference did not exist in cooked breasts. No other differences were noted between EB and HYD or CA and HYD.

Myoglobin, hemoglobin, and cytochromes are water-soluble sarcoplasmic proteins largely responsible for meat color (Judge *et al.*, 1989). Native, reduced myoglobin (oxymyoglobin and deoxymyoglobin) is characterized as a red to dark red pigment. Cooking denatures myoglobin producing the brown pigment hemichrome (Fox, 1987). Because of denaturation of the meat pigments, cooking may have reduced the color differences noted between treatments in the raw breasts. Additionally, the darker color of the HYD breasts compared with EB and CA may be related to the higher cooking loss of the HYD breasts. Pale pork color is associated with a high amount of free water that reflects light (Fox, 1987). There may have been less surface water in the HYD to reflect light resulting in a darker color.

The CA breasts follow the same pattern for cooked color as raw color in which the bone side was more ($P < 0.05$) red and more ($P < 0.05$) yellow than the skin side breast (Table 9). The EB breasts were also more red ($P < 0.05$) on the bone side compared with the skin side (Table 9). This difference was not determined in the raw breasts. Although there were differences in CIE L* and

b* values in raw breasts, there were no differences ($P > 0.05$) in the cooked EB breasts between locations. The HYD breasts were characterized as more ($P < 0.05$) red and darker ($P < 0.05$) on the bone side compared with the skin side (Table 9). This darkness difference was not measured in the raw HYD breasts. In addition, the difference in yellowness between HYD location in the raw breasts was not apparent in the cooked breasts.

SUMMARY AND CONCLUSIONS

Based on shear values, the Hydrodyne process may be used to tenderize (19.1 to 28.3% improvement) EB broiler breasts. The explosive level and distance combination of 350 g at 20 cm produced a product with similar shear values to CA. However, this level of treatment was not sufficient to improve EB breast tenderness to a level equivalent to CA based on sensory response of an experienced panel. Plumpness was decreased in Hydrodyne-treated breasts as compared with the thick EB breasts. Cooking reduced the color differences between treatments in raw breasts. The purge loss was not affected by the Hydrodyne process or deboning treatment. Higher pressure fronts may be necessary to increase the efficacy of improving EB broiler breast tenderness. If successful, poultry processors would benefit financially from the reduction or elimination of the standard broiler breast aging time of 4 to 6 h.

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