The Hydrodyne Process for Tenderizing Meat

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Introduction

The evolutionary process to improve meat tenderness has been a major focus of the meat industry and researchers for many years. A variety of techniques have been introduced for tenderizing meat. Techniques, applied individually or in combination have included tenderizing enzymes or ingredients to enhance enzyme activity, long time aging of chilled carcasses, short-time aging by elevating the temperature of chilled carcasses, storage of carcasses at room temperature prior to chilling, electrical stimulation of the hot carcass, selected separations (cuts) along the vertebral column and pelvic area, alternative carcass positioning, and pressure-heat treatments.

Godfrey disclosed a method and apparatus for tenderizing meat using an explosive charge in a patent in 1970. The method described would generate and apply a shock wave pressure front in liquid medium at velocities exceeding the speed of sound. It stated that the meat would be placed in a protective wrapping such as a flexible bag, from which the air was evacuated. While the principle behind the Godfrey patent was sound, the embodiments disclosed, such as the apparatus (tank) and position of the meat in relation to the tank and explosive charge presented serious difficulties in the potential for commercial tenderizing of meat. Meat would be thrown against the tank walls or into the tank cover. The Godfrey system never achieved actual utilization as far as we know.

The Hydrodyne process and equipment (patented by Long in 1993-94) was designed to overcome the deficiencies in the Godfrey patent. The Hydrodyne process uses a small amount of explosive to generate a supersonic, hydrodynamic shock wave pressure front in liquid medium (water). The shock wave with targeted pressure fronts of 10,000 psi, occurs in fractions of a millisecond and passes through objects in the water that are an acoustical (mechanical impedance) match with the water (Kolsky, 1980). Meat (muscle tissue), which compositionally is approximately 75% water, depending on the amount of intramuscular fat and connective tissue present (Price and Schweigert, 1978), is a close acoustical match. The shock wave reflects off any object in the water that is not an acoustic match with the water (Kolsky, 1980).

A series of experiments were conducted to determine the effectiveness of the Hydrodyne process on tenderizing meat from beef, pork and lamb. Experiments were initially conducted in 208-L capacity plastic containers with 51-cm diameters. Additional experiments were conducted in a larger (1060-L capacity with a 122-cm diameter), commercially designed stainless steel tank.

Experimental Procedures

In the initial experiments conducted in 208-L containers, the meat was encapsulated twice, first in a polyolefin resin (Cryovac®) bag followed by encapsulation in a polymer of isoprene (rubber) bag. Both bags were evacuated. Meat samples were supported against the floor of the containers which were fitted with a 2-cm thick, flat steel plate. The containers were situated below ground level and filled to the top with water. The explosive used was composed of a liquid (nitromethane) and a solid (ammonium nitrate). The explosive was submerged in the water to a distance of 30.5 cm away from the front surface of the meat and was wired to a detonating device. The detonating device triggered the detonation of the explosive. In the larger (1060-L) tank, meat (encapsulated only once in either polyolefin or puncture and abrasion resistant type bags) was placed on the bottom of the hemisphere shaped tank. The tank was filled with water and an explosive charge immersed in the water to a specified distance away from the bottom of the tank.

Beef Studies - Small Containers: In the first experiment (Solomon et al., 1997a) using the 208- L containers, 12 longissimus (LM) steaks (3.2 cm in thickness) were removed from the loins (both sides) of five 2-yr-old Holstein cows at 24 h postmortem. Two steaks served as controls from each loin. Six steaks per loin (two for each treatment) were exposed to the Hydrodyne process using either 50, 75, or 100 g of explosive in a single load. An additional two steaks per loin were exposed to the Hydrodyne process using two individual loads of 50 g of explosive each, the first detonation followed by a second. Steaks were cooked for shear force determinations.

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In a second experiment (Solomon et al., 1997a), portions of (n=8) boneless LM, biceps femoris (BF), semimembranosus (SM), and semitendinosus (ST) muscles from four 2-yr-old Holstein cows were hot-boned within 1.5 h postmortem, vacuum-packaged, and stored for 1 d at 2°C, after which they were frozen at -34°C. All muscles were thawed prior to sampling and treating with the Hydrodyne process which was performed within 24 h of thawing. Each muscle was divided into two equal portions, one portion (random) from each muscle was exposed to the Hydrodyne process (100 g of explosive) and the remaining portion from the same muscle served as the control. Steaks (3.2 cm in thickness) were cooked for shear force determinations

In a third experiment (Solomon et al., 1997c), four matched pairs of 3-d postslaughter U.S. Choice grade boneless strip loins (LM) were equally divided into the following treatments: control-3-d-aged; Hydrodyne at 3-d-aged with 100 g explosive in 208-L containers; aged-17-d; aged-21-d; aged-28-d and aged-35-d to determine compare the effect of Hydrodyne treatment to that of aging meat. Steaks (2.5 cm in thickness) were cooked for shear force determinations.

In a fourth experiment (Zuckerman and Solomon, 1998) using the 208-L containers, boneless strip loins (U.S. Select grade; 5-d postmortem) were cut into portions with the rib end and loin end randomly assigned to either the Hydrodyne treatment (100 g of explosive) or control. Muscle samples were removed from the treated and control samples (within 30 min) after Hydrodyne treatment for transmission electron microscopy evaluation. Steaks (2.5 cm in thickness) were cooked for shear force determinations.

In a fifth experiment consisting of two parts (Berry et al., 1997) using the 208-L containers, part 1: previously frozen boneless beef strip loins (U.S. Select grade n=4 carcasses) were cut into portions with the rib end and loin end randomly assigned to either the Hydrodyne process (100 g of explosive) or control. Part 2: fresh boneless strip loins (U.S. Select grade n=7 carcasses) were divided into equal sections with one section/loin subjected to the Hydrodyne process (80 g explosive 30.5 cm from the meat). Steaks (2.5 cm in thickness) from each experiment were evaluated for sensory properties by a 10-member trained panel for shear force.

Beef Studies - Large Tank: In the first experiment in the large tank (Solomon et al., 1997b), LM muscles from five 2-yr-old Holstein cows were hot-boned (within 1 h postmortem), vacuum packaged, held for 1-d at 2°C and then frozen (-34°C). Two steaks (2.5 cm in thickness) were removed from each LM and served as controls. The remaining portion was subsequently cut into four sections, repackaged and randomly assigned to be treated (Hydrodyne) with one of four different quantities of explosive (125, 160, 192, or 350 g). Each explosive treatment was submerged to a distance of 56-cm from the front face of the meat samples lying on the bottom of the tank.

In a second experiment in the large tank, LM muscles from six 2-yr-old Holstein cows excised from each carcass at 24 h postmortem were divided into portions and treated with 350 g of explosive at 56-cm from the meat surface or served as controls (Solomon et al., 1997d). Steaks (2.5 cm in thickness) were cooked for shear force determinations.

In a third experiment in the large tank, LM and SM muscles from 32 U.S. Select grade carcasses 7-d postmortem were divided into equal portions in order to treat each LM with one of the following treatments (control; 150 g at a distance of 56 cm from the front face of the meat; 350 g at a distance of 56 cm from the front face of the meat or 350 g at a distance of 46 cm from the front face of the meat. The SM muscles received one of the following treatments (control; 150 g at a distance of 56 cm from the meat; 350 g at a distance of 56 cm from the meat). Steaks (2.5 cm in thickness) were cooked for shear force determinations.

Pork Studies - Small Containers: Two studies (Solomon et al., 1996; 1997d) were performed both using boneless loins (n=24/study). Each loin was divided into two sections with one portion being treated with the Hydrodyne process (100 g explosive) using the 208-L containers while the remaining section served as controls. In both studies meat samples were treated with the Hydrodyne process after 1-d postslaughter. Three (2.5 cm in thickness) chops from each treatment were removed packaged and stored frozen for subsequent shear force determinations. In the first study the remaining portions (both Hydrodyne and control treatments) were vacuum packaged and stored at 4°C for 40 d. Purge loss and shear force were measured after this 40 d period.

Lamb Studies - Small Containers: LM and ST muscle samples from normal (n=16) and callipyge (n=16) wether lambs were subdivided so that one portion of each muscle would be treated with the Hydrodyne process while the remaining portion served as the control (Solomon et al., 1998). 100 g of explosives in the 208-L capacity containers was used for the Hydrodyne process. Chops (2.5 cm in thickness) were cooked for shear force determinations.

Cooking and Shear Force: In all the beef experiments except the Berry et al. (1997) study, the control and Hydrodyne samples were broiled to an internal temperature of 71°C (AMSA, 1995) using Farberware Open-Hearth broilers. In the Berry et al. (1997) study all steaks were cooked using Farberware Combination Convection Broiler Ovens (broiler mode only). Internal temperature was monitored using iron-constantan thermocouples attached to a multipoint recording potentiometer. For the pork and lamb studies, chops were broiled to internal temperatures of 71°C (AMSA, 1995) using Farberware Open-Hearth broilers. After cooking, all steaks and chops were allowed to cool to room tempera-

Table 1. Effect of quantity of explosive (small containers) on tenderization of beef longissimus muscle as measured by shear force

Quantity of explosive, g	No. of detonations	Shear force, kg
Control	0	7.8[a]
50	1	3.4[c,d]
50	2	2.2[d]
75	1	4.0[c]
100	1	2.6[d]
SEM		.3

[a,b,c,d]*Means within a column lacking a common superscript letter differ (P < .05). N = 10.*

ture (25°C) before coring. A minimum of eight cores (1.27-cm diameter) were removed from each steak and four to six cores from the chops parallel to the muscle fiber orientation for shear force determination using a Warner-Bratzler shear device mounted on a Food Texture Corp. Texture measurement system.

Results and Discussion

Beef Studies - Small Containers: In our initial set of experiments, small 208-L plastic containers were used, each fitted with a steel plate (2-cm thick). Results from the first test which evaluated three different loads (quantity) of explosive are presented in Table 1. Shear force was improved 49 to 72% using the Hydrodyne process. However, the magnitude of improvement depended on the quantity of explosive used or the number of detonations performed on each meat sample. Exposing pieces of meat to two independent loads of 50 g each resulted in the greatest improvement in shear force followed by the single 100 g load. Successful reductions in shear force were also achieved using single loads of either 50 or 75 g of explosives.

Table 2. Effect of the Hydrodyne process (small containers) on beef longissimus, semimembranosus, biceps femoris, and semitendinosus muscle shear force

	Shear force, kg			
Muscle	Control	Hydrodyne[b]	SEM	Significance, P <
Longissimus[a]	8.3	2.8	.4	.01
Semimembranosus[a]	10.5	4.3	.5	.01
Biceps femoris[a]	7.8	3.7	.3	.01
Semitendinosus[a]	12.9	5.7	.6	.01

[a]N = 8 [b]100 g

Hot-boning intact muscles (Table 2) and holding them for 1-d at 2°C before freezing resulted in high shear values (tough meat) that would suggest that "cold shortening" of the muscles occurred (Locker, 1985). In this study our intentions were to assure that meat samples representing four major beef muscles (LM, SM, BF, ST) of the carcass would be tough (high shear values). Results indicated that the Hydrodyne process was effective at significantly tenderizing "cold-shortened" meat, regardless of muscle origin. Improvements of 53 to 66% were observed.

Aging LM from U.S. Choice carcasses (Table 3) for two weeks or as much as five weeks reduced shear force by as much as 37% and as little as 24% compared to controls. There were no statistical differences (P>.01) among the different aging periods; all aging periods decreased (P<.01) shear values. The Hydrodyne process, which was performed at 3-d postslaughter (same time frame as the control samples), improved shear force 33%, which was equivalent in effectiveness in tenderizing as those found for the four aging periods evaluated.

In the fourth study, shear force for the U.S. Select beef longissimus samples (Table 4) representing the Hydrodyne treatment was 37% less than the shear force for the controls (3.4 vs 5.4 kg). At least part of the mechanism by which the Hydrodyne process increases tenderness in muscle instantaneously can be explained by the ultrastructural observations of the myofibrillar and associated proteins structure after undergoing the Hydrodyne treatment (Figure 1, a and b). Evaluation of the meat samples treated with the Hydrodyne process showed disruptions of myofibrils near and within the Z-line regions of the sarcomeres. The disintegrity of the I-band adjacent to Z-lines resulted in Z-line protein components being torn and remnants attached on either side of the fractures.

The Hydrodyne system uses a hydrodynamic shock wave to tenderize meat. Hydrodynamics, which occurs instantaneously, is the motion of fluids and the forces acting on solid bodies immersed in these fluids. The meat samples that are immersed in the water (fluid media) respond to the hydrodynamic shock wave as a result of possessing similar and dissimilar mechanical impedance characteristics as the liquid media (Kolsky, 1980).

Taste panel evaluations of U.S. Select beef longissimus muscles revealed that the only detectable differences

Table 3. Shear force of U.S. Choice beef longissimus muscles treated with the Hydrodyne process (small containers) or aged up to 35 days

	Control[c]	Hydrodyne[c,d]	Aged 17 d	Aged 21 d	Aged 28 d	Aged 35 d	SD
Shear force, kg	4.75[a]	3.17[b]	3.01[b]	3.50[b]	3.59[b]	3.15[b]	0.7

[a,b]*P < .01*
[c]*3-days postmortem*

Table 4. Effect of the Hydrodyne process (small containers) on U.S. Select beef longissimus[a] shear force

	Shear force, kg
Control	5.4[b]
Hydrodyne[d]	3.4[c]
SEM	.3

[a]*N = 3*
[b,c]*$P < .01$*
[d]*100 g*

(P<.05) were for tenderness scores (Table 5). Regardless of whether meat was previously frozen and thawed or fresh and never frozen, the Hydrodyne process improved meat tenderness scores as well as reduced shear force. No differences were detected between the Hydrodyne treated meat samples and controls for either panel flavor or juiciness scores for previously frozen and thawed or fresh meat samples.

Beef Studies - Large Tank: Results of the first experiment in the large commercial prototype tank using cold-shortened beef longissimus are presented in Table 6. Four different quantities of explosives were tested and results indicated that shear force was reduced 37-57% for Hydrodyne treated samples compared to controls. Control samples had initial shear values of 8.26 kg, suggesting cold-shortened meat

Table 5. Effect of the Hydrodyne process (small containers) on U.S. Select beef longissimus shear force and taste panel evaluations

	Fresh		Previously frozen	
Item	Control	Hydrodyne[a]	Control	Hydrodyne[b]
Shear force, kg	4.26	3.27[*]	2.81	2.09[*]
Panel tenderness	5.9	6.4	6.1	7.0[*]
Panel flavors	4.4	4.5	4.4	4.4
Panel juiciness	5.3	5.1	5.4	5.2

[a]*80 g*
[b]*100 g*
[*]*$P < .05$*

(Locker, 1985). Shear values for Hydrodyne treated samples were 5.21, 4.56, 4.39 and 3.52 kg for the 125, 160, 192, and 350 g of explosive all at 56-cm from the meat surface, respectively.

In the second experiment in the large tank (Table 7), LM muscles from 2-yr-old Holstein cows with initial (control) shear values of 6.57 kg and treated with 350 g of explosive at 56-cm from the meat improved 35% in shear force tenderness to 4.32 kg after Hydrodyne treatment.

In the third experiment (Table 8), both quantity and distance of the explosive from the meat surface were evaluated. Two different quantities (150 and 350 g) of explosive and two different distances 56 and 46 cm were examined. Decreasing the distance of explosive charge from 56 to 46

Figure 1a. Control-5-day postmortem beef longissimus muscle.
1b. Hydrodyne at 5-day postmortem beef longissimus.

Table 6. Effects of quantity of explosive (large tank) on tenderization of beef longissimus muscle[a] as measured by shear force

Quantity of explosive, g[b]	Shear force, kg
Control	8.26[c]
125	5.21[d]
160	4.56[d,e]
192	4.39[d,e]
350	3.52[d,e]
SEM	.4

[a]N = 10
[b]Explosive at 56-cm from meat surface
[c,d,e]P < .01

Table 7. Effect of the Hydrodyne process (large tank) on beef longissimus[a] shear force

	Shear force, kg
Control	6.57[c]
Hydrodyne[b]	4.32[d]
SEM	.4

[a]N = 12
[b]350 g at 56-cm from meat surface
[c,d]P < .01

cm had more of an effect in reducing shear force than increasing the quantity of explosive. Both variables will increase the pressure front transmitted in the tank upon detonation. Based on pressure curve equations derived for the two part explosive used in these experiments, 150 g at 56-cm would generate approximately 5500 psi of pressure at the front of the meat. 350 g at 56-cm would yield approximately 7500 psi of pressure while 350 g at 46-cm would generate approximately 10,400 psi of pressure. This would explain the increase in response/improvement observed when the explosive charge was brought closer to the meat as compared to simply increasing the quantity of explosive by 200 g.

Pork Studies - Small Containers: In the first of two experiments for pork (Table 9), 100 g of explosives reduced loin chop shear force from 4.24 to 3.51 kg. Aging the Hydrodyne samples for 40 days (postmortem) after being treated with the Hydrodyne process had no additional effect on improving shear force tenderness (3.63 kg). Aging control samples for 40 days reduced shear force from 4.24 to 3.69 kg, which was similar to the improvement found for the Hydrodyne samples treated at 1-d postmortem. Additionally, the Hydrodyne process decreased purge loss by 14% after 40 days of storage (2.5% purge loss) compared to control samples (2.9% purge loss) held for the same 40 day period.

In the second study (Table 9), initial, control shear force values were 5.63 kg and 100 g of explosive for the Hydrodyne treatment resulted in a 33% reduction in shear force compared to the controls (Hydrodyne treated = 3.76 kg).

Table 8. Effect of the Hydrodyne process (large tank) on U.S. Select beef longissimus (LM) and semimembranosus (SM) shear force

	Shear force, kg
LM[a]	
Control	4.64[b]
150 g at 56-cm from meat	4.08[b,c]
350 g at 56-cm " "	3.84[b,c]
350 g at 46-cm " "	3.35[d]
SEM	.2
SM[a]	
Control	5.28
150 g at 56-cm from meat	5.25
350 g at 56-cm " "	4.79
SEM	.4

[a]N = 32
[b,c,d]P < .01

Table 9. Effect of the Hydrodyne[a] process (small containers) on pork longissimus[b] shear force

	Shear force, kg
Study I	
Control 1-d	4.24[c]
Hydrodyne 1-d	3.51[d]
Control 40-d	3.69[d]
Hydrodyne 40-d	3.63[d]
SEM	.2
Study II	
Control 1-d	5.63[c]
Hydrodyne 1-d	3.76[d]
SEM	.3

[a]100g
[b]N=24
[c,d]P<.05

Lamb Studies - Small Containers: The effectiveness of the Hydrodyne process for tenderizing LM and ST muscles from callipyge and normal lambs was evaluated (Table 10). 100 g of explosive reduced shear values from 33 to 67% for LM muscles from callipyge and normal lambs, respectively. Shear force was reduced from 6.42 to 4.26 kg in callipyge LM and from 5.70 to 1.90 kg in control LM after using the Hydrodyne.

Conclusions

The Hydrodyne process has been shown to be effective at instantaneously improving meat tenderness in beef, pork and lamb. When compared to conventional aging tenderization the Hydrodyne process was as effective as aging. Tenderization occurs in fractions of a millisecond. When energy, space, and labor costs are considered for aging meat with or without additional postmortem tenderization treatments, the Hydrodyne process may offer a new alternative for tenderizing meat.

Table 10. Effect on the Hydrodyne[a] process (small containers) on lamb longissimus[b] and semitendinosus[b] shear force

Shear force, kg	Phenotype Normal	Callipyge	SEM
Longissimus			
Control	5.70[c]	6.42[c]	.56
Hydrodyne	1.90[d]	4.26[d]	.34
Semitendinosus			
Control	3.15	4.11	.38
Hydrodyne	2.96	3.67	.31

[a] *100g*
[b] *N=16*
[c,d] *P<.01*

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