Effects of zilpaterol hydrochloride and zinc methionine on growth performance and carcass characteristics of beef bulls

Miguel A. Rodríguez-Gaxiola[1], Ignacio A. Domínguez-Vara[1,4], Rubén Barajas-Cruz[2], María A. Mariezcurrema-Berasain[1], José L. Bórquez-Gastelum[1], and Billy J. Cervantes-Pacheco[3]

[1]Universidad Autónoma del Estado de México, Facultad de Medicina Veterinaria y Zootecnia, Departamento de Nutrición Animal, Campus Universitario "El Cerrillo", Toluca, Estado de México, CP. 50090; [2]Universidad Autónoma de Sinaloa, Facultad de Medicina Veterinaria y Zootecnia, Gral. Ángel Flores Pte. S/N Col. Centro, 8000 Culiacán, Sinaloa, México; and [3]Ganadera Los Migueles, S.A. de C.V. Culiacán, Sinaloa, México.
Received 16 November 2014, accepted 16 July 2015. Published on the web 10 August 2015.

Rodríguez-Gaxiola, M. A., Domínguez-Vara, I. A., Barajas-Cruz, R., Mariezcurrema-Berasain, M. A., Bórquez-Gastelum, J. L. and Cervantes-Pacheco, B. J. 2015. **Effects of zilpaterol hydrochloride and zinc methionine on growth performance and carcass characteristics of beef bulls**. Can. J. Anim. Sci. **95**: 609–615. Sixty beef bulls with a body weight (BW) of 314.7 ± 16.2 kg were used to evaluate the effects of zilpaterol hydrochloride (ZH) and zinc methionine (ZM) on growth performance and carcass characteristics. The experimental design was a randomized complete block, with a factorial 2 × 2 arrangement of treatments (ZH: 0 and 0.15 mg kg^{-1} BW; ZM: 0 and 80 mg kg^{-1} dry matter). The ZH increased ($P < 0.05$) the final BW, average daily gain, feed conversion, carcass yield and longissimus dorsi area. Bulls fed ZH plus ZM had less ($P < 0.01$) backfat thickness and intramuscular fat (IMF) compared with those fed ZH or ZM alone. The ZH increased ($P < 0.02$) the meat crude protein content and cooking loss. It is therefore concluded that ZH increases growth performance, carcass yield, longissimus dorsi area, and meat crude protein. The interaction of ZM and ZH did not present additional advantages. The reason for the reduction in backfat thickness and IMF by ZH plus ZM is unclear, and implies that our knowledge of β-agonistic adrenergic substances and their interactions with minerals is incomplete.

Key words: Beef bulls, zilpaterol hydrochloride, zinc methionine

Rodríguez-Gaxiola, M. A., Domínguez-Vara, I. A., Barajas-Cruz, R., Mariezcurrema-Berasain, M. A., Bórquez-Gastelum, J. L. et Cervantes-Pacheco, B. J. 2015. **Les effets du chlorhydrate de zilpatérol et de la méthionine de zinc sur les performances de croissance et caractéristiques de carcasse des taureaux de boucherie**. Can. J. Anim. Sci. **95**: 609–615. Soixante taureaux de boucherie de poids corporel (BW – « body weight ») 314,7 ± 16,2 kg ont été utilisés pour évaluer les effets du chlorhydrate de zilpatérol (ZH – « zilpaterol hydrochloride ») et du méthionine de zinc (ZM – « zinc methionine ») sur les performances de croissance et les caractéristiques de carcasse. Le design expérimental était un bloc aléatoire complet, avec un arrangement factoriel de 2x2 traitements (ZH : 0 et 0,15 mg kg^{-1} BW; ZM : 0 et 80 mg kg^{-1} matières sèches – DM – « dry matter »). Le ZH a augmenté ($P < 0,05$) le BW final, le gain moyen quotidien, l'indice de consommation, le rendement de carcasse et l'aire du muscle longissimus dorsi. Les taureaux nourris de ZH et de ZM avaient une plus faible ($P < 0,01$) épaisseur de gras dorsal et de gras intramusculaire (IMF – « intramuscular fat ») par rapport aux taureaux nourris de ZH seulement ou ZM seulement. Le ZH a augmenté ($P < 0,02$) la teneur en protéines brutes de la viande et les pertes à la cuisson. Par conséquent, on peut conclure que le ZH augmente la performance de croissance, le rendement de la carcasse, l'aire du muscle longissimus dorsi et le taux de protéines brutes de la viande. L'interaction de ZM et de ZH ne présente pas d'avantages supplémentaires. La réduction de épaisseur de gras dorsal et du IMF par ZM et ZH ensemble demeure incomprise et souligne que nos connaissances des substances β-agonistes adrénergiques et leurs interactions avec les minéraux sont encore incomplètes.

Mots clés: Taureaux de boucherie, chlorhydrate de zilpatérol, méthionine de zinc

Zilpaterol hydrochloride (ZH) is an adrenergic β-agonist that in some countries, such as Mexico, the United States, South Africa and Canada, is used as a feed additive to increase the carcass dressing of beef cattle (Delmore et al. 2010). Zilpaterol hydrochloride induces lipolysis and redirects energy towards protein synthesis, which leads to muscle hypertrophy (Helferich et al. 1990; Mersmann 1998), although some studies have indicated that ZH reduces meat tenderness (Garmyn et al. 2010; Bohrer et al. 2014). Since one of the attributes that has an

Abbreviations: **BW**, body weight; **DM**, dry matter; **DMI**, dry matter intake; **HCW**, hot carcass weight; **IMF**, intramuscular meat fat; **KPH**, fat in kidney, pelvis and heart; **ZH**, zilpaterol hydrochloride; **ZM**, zinc methionine

[4]*Corresponding author (e-mail: igy92@hotmail.com).*

impact on the satisfaction of beef consumers is tenderness and because this can be enhanced by an increased intramuscular fat (IMF) content (Brooks et al. 2010), it is important to look for alternatives that allow an increase IMF in beef cattle fed ZH. Zinc is an essential trace element that is related to the metabolism of carbohydrates, proteins, lipids and nucleic acids (Smith and Akinbamizo 2000; Vierboom et al. 2003). Zinc has been related to several mechanisms, such as being a lipogenic compound (Malcom-Callis et al. 2000; Oh and Choi 2004), stimulating lipogenesis and inhibiting lipolysis (Coulston and Dandona 1980; May and Contoreggi 1982) through insulin signaling (May and Contoreggi 1982; Saltiel and Kahn 2001; Eom et al. 2001; Park et al. 2003). Adding Zn to diets favors the deposition of fat and the degree of marbling in meat of feedlot cattle (Greene et al. 1988; Spears and Kegley 2002). Adding organic Zn produces better results than inorganic sources (Malcom-Callis et al. 2000; Spears and Kegley 2002; Nunnery et al. 2007). The National Research Council (NRC 1996) recommends 30 mg Zn kg^{-1} dry matter (DM) for fattening cattle. In practice, nutritionists from United States and Brazil use from 49 to 93 mg Zn kg^{-1} DM (Vasconcelos and Galyean 2007; Millen et al. 2009). Nunnery et al. (2007) found that the best productive response in fattening steers was obtained with 75 mg Zn kg^{-1} DM. Therefore, our hypothesis is that ZH plus zinc methionine (ZM) may increase the growth performance, IMF, meat tenderness and carcass characteristics of beef bulls. The objective of this study was to evaluate the effects of zilpaterol hydrochloride and zinc methionine on the growth performance and carcass characteristics of beef bulls.

MATERIALS AND METHODS

This research project was approved by the Bioethic and Animal Welfare Committee of Facultad de Medicina Veterinaria y Zootecnia of the Universidad Autónoma del Estado de México, and followed principles established by the Canadian Council on Animal Care (1993). The feedlot trial and carcass evaluation were carried out in the feedlot facilities of the Facultad de Veterinaria y Ciencia Animal, Universidad Autónoma de Sinaloa in Culiacan, México. Meat evaluations and feed analysis were carried out in the Departamento de Nutrición Animal, Facultad de Medicina Veterinaria y Zootecnia, Universidad Autónoma del Estado de México in Toluca, México.

Animals and Treatments

Sixty 13-mo-old crossbreed bulls, 50% Brahman and 50% European cattle, with a body weight (BW) of 314.7 ± 16.2 kg were selected. Bulls were vaccinated (One Shot of Ultrabac-Somnubac; Pfizer Ltd), implanted (Component TE-S implant with Tylan, Elanco Animal Health) and dewormed (Albendaphorte PLUS, Lab Salud y Bienestar Animal S.A. de C.V. México). Based on the initial BW, bulls were grouped into three blocks (heavy 349.8 ± 18.2 kg, medium 322.2 ± 3.9 kg, and light 311.6 ± 3.6 kg BW). Each block had four pens with five bulls in each. Pen (6 × 12m) was considered the experimental unit ($n = 12$). Pens were equipped with a bunk feeder and an automatic drinking trough. Bulls were fed once a day (1500) with a basal diet (Table 1).

Within each block, the treatments were randomly assigned as follow: (1) control, (2) ZH, (3) ZM, and (4) ZH + ZM. Bulls were fed ZH (Zilmax®, Merck Animal Health, Summit, NJ) at 0.15 mg kg^{-1} 33 d before programmed harvesting date, and was withdrawn from the diet 72 h before cattle were harvested. Doses of ZH and ZM were calculated daily and mixed with 1 kg of ground corn, which was hand-mixed with the top third of the basal diet contained in the feed bunk, using the "top dress" technique, immediately after diet was delivered. Bulls were fed once daily (1500) and enough feed was offered to provide 5% feed refusal. Diet offered and diet refused were measured daily. Diet was sampled weekly from the feed mixer wagon (Tormex 1200, Torreón, Mexico) and composited by month. Diet and refusals were analyzed for DM (65°C oven 24 h) and this was used for DM intake (DMI) calculations. Feed samples were analyzed for Kjeldahl N × 6.25 [method 976.05, Association of Official Analytical Chemists (AOAC) 2007] and neutral detergent fiber [Van Soest et al. (1991) modified for Ankom^{200} fiber analyzer, Ankom Technology, Fairport, NY].

Bulls were weighted at day 1 and day 88. For initial BW (day 1), 4% was subtracted from their weight as fill of digestive tract (NRC 1996). Final BW (day 88) was obtained immediately after insensibility was induced in the slaughterhouse.

Table 1. Dietary ingredients used and final chemical composition of basal diet

Ingredient composition (g kg^{-1} DM)	
Corn stover	110.9
Ground corn grain	716.2
Cotton seed meal	55.5
Cane molasses	67.2
Tallow	22.2
Vitamins and minerals premix[z]	28.0
Nutrient composition (g kg^{-1} DM)	
CP (g kg^{-1} DM)	133.0
NDF (g kg^{-1} DM)	15.6
ENg (MJ kg^{-1} DM)[y]	5.86
Zn (mg kg^{-1} DM)[y]	73.28

[z]Premix: microminerals (mg kg^{-1}) I, 20; Se, 8; Co, 4; Cu, 160; Zn, 2000; Mn, 1200; Fe, 800; macrominerals (%) S, 0.18; P, 0.80; Ca, 21.28; Na, 4.72; Cl, 7.28. Vitamin A, 64 000 IU kg^{-1}; vitamin E, 20 000 IU kg^{-1}; vitamin D, 300 IU kg^{-1}; CP, 112.8% (NNP from urea; 2.8 × 1.128 = 3.16% CP to basal diet and 1 g kg^{-1} of sodium monensin from Rumensin 200® (Elanco Animal Health).

[y]Values according to nutrient requirements for beef cattle (National Research Council 1996).

Carcass Characteristics

Once the feedlot period ended, bulls were transported by truck (27 km) to the processing plant TIF-99 (FAPSA y Asociados, S.A. de C.V. México), and slaughtered following established standards. Carcasses were weighted immediately after slaughter; hot carcass weight (HCW) was obtained and carcass dressing was calculated as the final BW to HCW ratio. After 24 h chilling at 4°C, a cross cut was performed in the longissimus dorsi of the left side of the carcass, between the 12th and 13th ribs, and left for 15 min to allow solidification of the internal fat. The meat color was measured with a colorimeter (Minolta Chromameter CR-200, using the CIELAB color space), pH and temperature were measured with a potentiometer fitted with a penetration electrode (HANNA model HI 99163), backfat thickness (mm) was measured with a digital vernier (Absolute Digimatic 500, Mitutoyo Corporation; Japan), the longissimus dorsi area was measured with a United States Department of Agriculture template (USDA 2011), degree of marbling of the meat was determined visually (reference photographs; USDA 2006) based on a 10-point scale (100 = devoid; 200 = practically devoid; 300 = trace; 400 = slight; 500 = small; 600 = modest; 700 = moderate; 800 = slightly abundant; 900 = moderately abundant; and 1000 = abundant), and fat around the kidney, pelvis and heart was estimated as a percentage of the carcass weight (USDA 1997).

Meat Quality Trait

Twenty-four carcasses were used for the meat quality analysis (eight carcasses per block and two carcasses per treatment in each block). Each carcass was considered as the experimental unit, and then the study for meat quality had six repetitions by treatment and, consequently, 12 repetitions by each main factor.

A primal rib section based on lean muscle and fat from ribs 10 to 14 was removed from the left side of each carcass. Four 2.5-cm-thick steaks were obtained from the primal rib section and weighed individually; a 50-g sample was taken for immediate determination of capacity for water retention by compression between two plates (Honikel 1998), and then the steaks were vacuum packaged and frozen (-20°C) for subsequent analyses. The DM content, ash, protein and fat were determined according to AOAC (2007). The shear force was determined with a Warner–Bratzler blade and the loss due to cooking was estimated by gravimetric methods (American Meat Science Association 1995).

Statistical Analysis

Growth performance, carcass characteristics and meat quality data were analyzed statistically as a randomized complete block design with a 2×2 factorial arrangement of treatments (ZH: 0 and 0.15 mg kg^{-1} BW; ZM: 0 and 80 mg kg^{-1} DM) using PROC MIXED (SAS Institute Inc. 2006) with a model that included block (random), ZH (fixed), ZM (fixed) and ZH × ZM interaction (fixed). The SLICE option (SAS Institute Inc. 2006) was used when a two-way interaction was found at $P \leq 0.05$.

RESULTS AND DISCUSSION

Growth Performance

The final BW and average daily gain of bulls fed ZH were, respectively, 4.8 and 17.6% higher ($P = 0.05$) than bulls on the control treatment or fed the ZM diet.

Treatments did not affect DMI ($P > 0.05$); thus, feed conversion was increased ($P < 0.01$) 14.8% (Table 2). Growth performance, DMI and feed conversion were not affected ($P > 0.05$) by ZM, and there was no interaction ($P > 0.05$) between ZH and ZM treatments. The increased weight gain found with the use of ZH in cattle and sheep (Montgomery et al. 2009; Mondragón et al. 2010; McEvers et al. 2014) could be due to an increase in muscle protein synthesis and a decrease in muscle protein turnover (Helferich et al. 1990; Johnson et al. 2014). The anabolic activity of ZH is mediated by an enhancement in cAMP activity (Mersmann 1998), and this can cause an increase in mRNA that codifies for myosin heavy chain-IIX and IIB in the bovine muscle cell (Baxa et al. 2010; Hemmings et al. 2014). In agreement with our results, previous studies with cattle and sheep have shown beneficial effects of ZH on feed conversion (Avendaño-Reyes et al. 2006; McEvers et al. 2014; Bohrer et al. 2014) as a result of increase in weight gain, with no effect on DMI (Mondragón et al. 2010; Lawrence et al. 2011; Parr et al. 2011).

Table 2. Effect of zilpaterol hydrochloride and zinc methionine on the growth performance of beef bulls

	−ZH[z]		+ZH[z]			Effect[x]		
Item	−ZM	+ZM	−ZM	+ZM	SEM[y]	ZH	ZM	ZH × ZM
Initial body weight (kg)	314.4	314.6	314.9	314.8	13.40	–	–	–
Final body weight (kg)	470.4	497.0	465.2	483.2	9.89	0.05	NS	NS
Dry matter intake (kg d^{-1})	10.8	10.6	11.0	10.7	0.38	NS	NS	NS
Average daily weight (kg d^{-1})	1.7	2.0	1.7	1.9	0.11	0.02	NS	NS
Feed conversion (kg)	6.35	5.30	6.47	5.63	0.25	0.01	NS	NS

[z] −ZH, zilpaterol hydrochloride at 0 mg kg^{-1} BW; +ZH, zilpaterol hydrochloride at 0.15 mg kg^{-1} BW; −ZM, zinc methionine at 0 mg kg^{-1} DM; +ZM, zinc methionine at 80 mg kg^{-1} DM.
[y] SEM, standard error of the mean.
[x] NS, not significant at $P > 0.05$.

Table 3. Effect of zilpaterol hydrochloride and zinc methionine on carcass characteristics of beef bulls

	−ZH[z]		+ZH[z]			Effect[x]		
Item	−ZM	+ZM	−ZM	+ZM	SEM[y]	ZH	ZM	ZH × ZM
Hot carcass weight (kg)	283.5	305.5	278.3	297.8	2.39	0.01	NS	NS
Hot carcass dressing (%)	60.2	61.4	59.8	61.6	0.97	0.05	NS	NS
Longissimus dorsi area (cm^2)	70.5	76.7	69.7	67.9	1.02	0.01	NS	NS
Kidney, pelvis and heart fat (%)	1.7	2.0	2.4	2.2	0.06	0.01	NS	NS
Marbling[w]	460.0	453.3	440.0	453.3	8.60	NS	NS	NS
pH at 24 h	6.3	6.0	5.9	5.9	0.02	0.01	0.01	0.02
Temperature at 24 h (°C)	2.8	2.1	2.4	2.6	0.10	0.02	0.01	NS
Meat color								
*L**	22.0	20.7	21.2	22.6	1.00	NS	NS	NS
*a**	2.4	2.7	3.5	2.3	0.45	NS	NS	NS
*b**	16.8	12.7	13.6	10.4	0.86	0.02	0.05	NS
Backfat thickness (mm)	5.6	7.5	8.4	6.2	0.441	NS	NS	0.01
Intramuscular meat fat (g kg^{-1} BH)	46.0	49.0	49.0	34.0	0.241	NS	NS	0.01

[z] −ZH, zilpaterol hydrochloride at 0 mg kg^{-1} BW; +ZH, zilpaterol hydrochloride at 0.15 mg kg^{-1} BW; −ZM, zinc methionine at 0 mg kg^{-1} DM; +ZM, zinc methionine at 80 mg kg^{-1} DM.
[y] SEM, standard error of the mean.
[x] NS, not significant at $P > 0.05$.
[w] Lacking = 300; light = 400; small = 500; modest = 600.

Carcass Characteristics

Hot carcass weight and dressing increased 7.4% ($P < 0.01$) and 2.5% ($P < 0.05$), respectively, with ZH compared with treatments without ZH (Table 3). This is in agreement with previous studies, which were within the range 4.0 to 5.7% for HCW and 1.8 to 2.6% for carcass dressing (Lawrence et al. 2011; Parr et al. 2011; McEvers et al. 2014). Several studies have reported increases in hot carcass dressing in steers fed β-adrenergic agonists (Schroeder et al. 2003; Avendaño-Reyes et al. 2006; Boler et al. 2012; Bohrer et al. 2014). Although some studies have reported no effect of β-adrenergic agonist on carcass dressing (Winterholler et al. 2007; Scramlin et al. 2010), increments for at least 1.5% in carcass dressing are commonly expected when zilpaterol hydrochloride is fed to beef cattle (Schroeder et al. 2003; Avendaño-Reyes et al. 2006). Bulls fed ZH had a 13.4% greater longissimus dorsi area compared with bulls not fed ZH; this may be due to the inhibition of protein turnover and promotion of the synthesis of myofibrillar protein, which causes muscle hypertrophy (Ricks et al. 1984; Johnson et al. 2014). An increase in longissimus dorsi area has been observed in many studies when ZH is fed to cattle (Montgomery et al. 2009; Lawrence et al. 2011; McEvers et al. 2014). Feeding ZH to beef cattle usually decreases fat content, both fat around the kidney, pelvis and heart and marbling fat (Johnson et al. 2014), but this was not observed in our study.

Meat pH was not affected ($P > 0.20$) by ZH or ZM. This agrees with other studies with beef steers (Avendaño-Reyes et al. 2006; Bohrer et al. 2014). Meat temperature was reduced ($P = 0.02$) by feeding ZH. The degree of fattening might be related to this effect, since adipose tissue provides protection from cold temperatures (Murray 1989); carcasses with less fat cover cool faster. Although no effect ($P = 0.75$) of ZH was found on backfat thickness, its distribution was not evaluated in this study.

The brightness and intensity of red color in the meat (color spaces *L** and *a**) were not affected ($P > 0.20$) by

Table 4. Effect of zilpaterol hydrochloride and zinc methionine on longissimus dorsi characteristics of beef bulls

	−ZH[z]		+ZH[z]			Effect[x]		
Item	−ZM	+ZM	−ZM	+ZM	SEM[y]	ZH	ZM	ZH × ZM
Dry matter (g kg^{-1})	267.8	274.8	260.8	260.9	3.62	NS	NS	NS
Ash (g kg^{-1})	13.9	13.8	14.6	14.0	0.04	NS	NS	NS
Protein (g kg^{-1})	221.6	236.5	215.8	227.3	3.43	0.01	NS	NS
Capacity for water retention (%)	92.6	92.7	92.7	92.8	0.60	NS	NS	NS
Cooking loss (%)	27.3	31.4	25.3	28.5	1.01	0.02	NS	NS
Shear force (kg cm^2)	9.2	10.0	9.3	7.7	0.67	NS	NS	NS

[z] −ZH, zilpaterol hydrochloride at 0 mg kg^{-1} BW; +ZH, zilpaterol hydrochloride at 0.15 mg kg^{-1} BW; −ZM, zinc methionine at 0 mg kg^{-1} DM; +ZM, zinc methionine at 80 mg kg^{-1} DM.
[y] SEM, standard error of the mean.
[x] NS, not significant at $P > 0.05$.

ZH or ZM, but the intensity of yellow (color space b^*) was reduced ($P = 0.02$) by ZH. A reduction in color intensity when ZH is included in the diet was reported by Hilton et al. (2009). The intensity of color is related to the oxidation of myoglobin to metamyoglobin (MacDougall 1977; Faustman et al. 2010). Because ZH reduces metamyoglobin content in meat (Montgomery et al. 2009), a reduction in color intensity by ZH is expected. Carcass characteristics were not affected ($P > 0.05$) by ZM, but interactions (Table 3) indicated that bulls fed ZH plus ZM had the lowest ($P < 0.01$) backfat thickness and IMF. Previous studies evaluated ZM effects on IMF thickness and backfat thickness in steers, but not the interaction ZH × ZM (Greene et al. 1988; Malcom-Callis et al. 2000; Spears and Kegley 2002). Zinc has a lipogenic effect (Tang and Shay 2001; Park et al. 2003; Vardatsikos et al. 2013) caused by inhibition of lipolytic substances (May and Contoreggi 1982; Oh and Choi 2004) and by changing expression of transcript factors and genes responsible for triglycerides and lipoproteins synthesis (Oh and Choi 2004). In addition, ZH inhibits the biosynthesis of de novo fatty acids and stimulates the hydrolysis of triacylglycerol (Oscar 1995; Johnson et al. 2014). Studies evaluating the interaction of ZH and ZM are limited, but Bohrer et al. (2014) reported that fat content of the carcass was not affected by supplementation of Zn propionate to beef steers fed ractopamine.

Meat Quality Traits

Protein content increased ($P < 0.01$) 5.9% with the addition of dietary ZH (Table 4). This was previously reported by Shook et al. (2009) and was attributed to greater muscle nitrogen retention induced by ZH (Helferich et al. 1990; Mersmann 1998). The cooking loss of meat was increased 13.7% ($P = 0.02$) by ZH. Because ZH increases the size of muscle cells, the support structure in meat could be modified (Holmer et al. 2009; Garmyn et al. 2011). Dry matter and ash content, the capacity for water retention and Warner–Bratzler shear force of meat were not affected ($P > 0.05$) by ZH or ZM treatments.

CONCLUSIONS

In this study, while ZH increased growth performance, carcass yield, longissimus dorsi area, and meat protein content, the inclusion of ZM in ZH-supplemented diets for feedlot beef bulls did not have an additional advantage. The cause of the reduction in IMF thickness and backfat thickness by ZH plus ZM is not clear, and implies that our knowledge of the action of β-agonistic adrenergic substances and their interactions with zinc methionine is incomplete.

ACKNOWLEDGMENTS

This research was financed by "Ganadera Los Migueles, S.A. de C.V." Universidad Autónoma del Estado de México, and Consejo Nacional de Ciencia y Tecnología, México.

American Meat Science Association. 1995. Research guidelines for cookery, sensory evaluation and instrumental tenderness measurements of fresh meat. AMSA, Champaign, IL.

Association of Official Analytical Chemists. 2007. Official methods of analysis of the Association of Official Analytical Chemists. 18th ed. AOAC, Arlington, VA.

Avendaño-Reyes, L. V., Torres-Rodríguez, F. J., Meraz-Murillo, C., Pérez-Linares, F., Figueroa, S. and Robinson, P. H. 2006. Effects of two β-adrenergic agonists on finishing performance, carcass characteristics, and meat quality of feedlot steers. J. Anim. Sci. **84**: 3259–3265.

Baxa, T. J., Hucheson, J. P., Miller, M. F., Brooks, J. C., Nichols, W. T., Streeter, M. N., Yates, D. A. and Johnson, B. J. 2010. Additive effects of a steroidal implant and zilpaterol hydrochloride on feedlot performance, carcass characteristics, and skeletal muscle messenger ribonucleic acid abundance in finishing steers. J. Anim. Sci. **88**: 330–337.

Bohrer, B. M., Edenburn, B. M., Boler, D. D., Dilger, A. C. and Felix, T. L. 2014. Effect of feeding ractopamine hydrochloride (Optaflexx) with or without supplemental zinc and chromium propionate on growth performance, carcass characteristic, and meat quality of finishing steers. J. Anim. Sci. **92**: 3988–3996.

Boler, D. D., Shreck, A. L., Faulkner, D. B., Killefer, J., McKeith, F. K., Homm, J. W. and Scanga, J. A. 2012. Effect of ractopamine hydrochloride (Optaflexx) dose on live animal performance, carcass characteristics and tenderness in early weaned beef steers. Meat Sci. **92**: 458–463.

Brooks, J. C., Mehaffey, J. M., Collins, J. A., Rogers, H. R., Legako, J., Johnson, J., Lawrence, T., Allen, D., Streeter, M. N., Nichols, W. T., Hutcheson, J. P., Yates, D. A. and Miller, M. F. 2010. Moisture enhancement and blade tenderization effects on the shear force and palatability of strip loin steaks from beef cattle fed zilpaterol hydrochloride. J. Anim. Sci. **88**: 1809–1816.

Canadian Council on Animal Care. 1993. Guide to the care and use of experimental animals. Volume 1. 2nd ed. E. D. Olfert, B. M. Cross, and A. A. McWilliam, eds. CCAC, Ottawa, ON.

Coulston, L. and Dandona, P. 1980. Insulin-like effect of zinc on adipocytes. Diabetes **29**: 665–667.

Delmore, R. J., Hodgen, J. M. and Johnson, B. J. 2010. Perspectives on the application of zilpaterol hydrochloride in the United States beef industry. J. Anim. Sci. **88**: 2825–2828.

Eom, S. J., Kim, E. Y., Lee, J. E., Kang, H. J., Shim, J., Kim, S. U., Gwag, B. J. and Choi, E. J. 2001. Zn (2^+) induces stimulation of the c-Jun N-terminal kinase signaling pathway through phospho-inositide 3-kinase. Mol. Pharmacol. **59**: 981–986.

Faustman, C., Sun, Q., Mancini, R. and Suman, S. P. 2010. Myoglobin and lipid oxidation interactions: Mechanistic bases and control. Meat Sci. **86**: 86–94.

Garmyn, A. J., Shook, J. N., VanOverbeke, D. L., Beckett, J. L., Delmore, R. J., Yates, D. A., Allen, D. M. and Hilton, G. G. 2010. The effect of zilpaterol hydrochloride on carcass cutability and tenderness of calf-fed Holstein steers. J. Anim. Sci. **88**: 2476–2485.

Garmyn, A. J., Knobel, S. M., Spivey, K. S., Hightower, L. F., Brooks, J. C., Johnson, B. J., Parr, S. L., Rathmann, R. J., Starkey, J. D., Yates, D. A., Hodgen, J. M., Hutcheson, J. P. and Miller, M. F. 2011. Warner–Bratzler and slice shear force measurements of 3 beef muscles in response to various aging periods after trenbolone acetate and estradiol implants and zilpaterol hydrochloride supplementation of finishing beef steers. J. Anim. Sci. **89**: 3783–3791.

Greene, L. W., Lunt, D. K., Byers, F. M., Chirase, N. K., Richmond, C. E., Knutson, R. E. and Schelling, G. T. 1988. Performance and carcass quality of steers supplemented with zinc oxide or zinc methionine. J. Anim. Sci. **66**: 1818–1823.

Helferich, W. G., Jump, D. B., Anderson, D. B., Skjaerlum, D. M., Merkel, R. A. and Bergen, W. G. 1990. Skeletal muscle β-actin is increased pretranslational in pigs fed the phenotholamine ractopamine. Endocrinology **126**: 3096–3100.

Hemmings, K. M., Daniel, Z. C. T. R., Buttery, T. J., Parr, T. and Brameld, J. M. 2014. Differential effects of short-term β agonist and growth hormone treatments on expression of myosin heavy chain IIB and associated metabolic genes in sheep muscle. Animal **9**: 285–294.

Hilton, G. G., Montgomery, J. L., Krehbiel, C. R., Yates, D. A., Hutcheson, J. P., Nichols, W. T., Streeter, M. N., Blanton, J. R., Jr. and Miller, M. F. 2009. Effects of feeding zilpaterol hydrochloride with and without monensin and tylosin on carcass cutability and meat palatability of beef steers. J. Anim. Sci. **87**: 1394–1406.

Holmer, S. F., Fernández-Dueñas, D. M., Scramlin, S. M., Souza, C. M., Boler, D. D., McKeith, F. K., Killefer, J., Delmore, R. J., Beckett, J. L., Lawrence, T. E., VanOverbeke, D. L., Hilton, G. G., Dikeman, M. E., Brooks, J. C., Zinn, R. A., Streeter, M. N., Hutcheson, J. P., Nichols, W. T., Allen, D. M. and Yates, D. A. 2009. The effect of zilpaterol hydrochloride on meat quality of calf-fed Holstein steers. J. Anim. Sci. **87**: 3730–3738.

Honikel, K. O. 1998. Reference methods for the assessment of physical characteristics of meat. Meat Sci. **49**: 447–457.

Johnson, J. B., Smith, B. S. and Chung, Y. K. 2014. Historical overview of the effect of β-adrenergic agonists on beef cattle production. Asian Australas. J. Anim. Sci. **27**: 757–766.

Lawrence, T. E., Gasch, T. E., Hutcheson, C. A. and Hodgen, J. P. 2011. Zilpaterol improves feeding performance and fabrication yield of concentrate-finished cows. J. Anim. Sci. **89**: 2170–2175.

MacDougall, D. B. 1977. Colour in meat. *In* G. G. Birch, J. G. Brennan, and K. Parker, eds. Sensory properties of foods. Applied Science Publishers, London, UK. 59 pp.

Malcolm-Callis, K. J., Duff, J. C., Gunter, S. A., Kegley, E. B. and Vermeire, D. A. 2000. Effects of supplemental zinc concentration and source on performance, carcass characteristics, and serum values in finishing beef steers. J. Anim. Sci. **78**: 2801–2808.

May, J. M. and Contoreggi, C. S. 1982. The mechanism of the insulin-like effects of ionic zinc. J. Biol. Chem. **257**: 4362–4368.

McEvers, T. J., Walter, L. C., DeFoor, P. J., Swingle, R. S., Hutcheson, J. P. and Lawrence, T. E. 2014. The effect of supplementing zilpaterol hydrochloride on feeding performance and carcass characteristics of steers sorted by leptin genotype. J. Anim. Sci. **92**: 332–338.

Mersmann, H. J. 1998. Overview of the effects of beta-adrenergic receptor agonists on animal growth including mechanisms of action. J. Anim. Sci. **76**: 160–172.

Millen, D. D., Pacheco, R. D., Arrigoni, M. D. B., Gaylean, M. L. and Vasconcelos, J. T. 2009. A snapshot of management practices and nutritional recommendations used by feedlot nutritionist in Brazil. J. Anim. Sci. **87**: 3427–3439.

Mondragón, J., Domínguez-Vara, I. A., Pinos-Rodríguez, J. M., González, M., Bórquez, J. L., Domínguez, A. and Mejía, M. L. 2010. Effects of feed supplementation of zilpaterol hydrochloride on growth performance and carcass traits of finishing lambs. Acta Agric. Scan. Anim. Sci. **60**: 47–52.

Montgomery, J. L., Krehbiel, C. R., Cranston, J. J., Yates, D. A., Hutcheson, J. P., Nichols, W. T., Streeter, M. N., Bechtol, D. T., Johnson, E., TerHune, T. and Montgomery, T. H. 2009. Dietary zilpaterol hydrochloride. I. Feedlot performance and carcass traits of steers and heifers. J. Anim. Sci. **87**: 1374–1383.

Murray, A. C. 1989. Factors affecting beef color at time of grading. Can. J. Anim. Sci. **69**: 347–355.

National Research Council. 1996. Nutrient requirements of beef cattle. 7th ed. National Academy Press, Washington, DC.

Nunnery, G. A., Vasconcelos, J. T., Parsons, C. H., Salyer, G. B., Defoor, P. J., Valdez, F. R. and Galyean, M. L. 2007. Effects of source of supplemental zinc on performance and humoral immunity in beef heifers. J. Anim. Sci. **85**: 2304–2313.

Oh, Y. S. and Choi, C. B. 2004. Effects of zinc on lipogenesis of bovine intramuscular adipocytes. Asian Austr. J. Anim. Sci. **17**: 1378–1382.

Oscar, T. P. 1995. Lipid mobilization from chicken fat cells. Pages 93–112 *in* S. B. Smith and D.R. Smith, eds. Biology of fat in meat animals: Current advances. American Society of Animal Science, Champaign, IL.

Park, K. S., Lee, N. G., Lee, K. H., Seo, J. T. and Choi, K. Y. 2003. The ERK pathway involves positive and negative regulations of HT-29 colorectal cancer cell growth by extracellular zinc. Am. J. Physiol. Gastrointest. Liver Physiol. **285**: 1181–1188.

Parr, S. L., Chung, K. Y., Galyean, M. L., Hutcheson, J. P., DiLorenzo, N., Hales, K., May, M. L., Quinn, M., Smith, D. and Johnson, B. 2011. Performance of finishing beef steers in response to anabolic implant and zilpaterol hydrochloride supplementation. J. Anim. Sci. **89**: 560–570.

Ricks, C. A., Dalrymple, R. H., Baker, P. K. and Ingle, D. L. 1984. Use of a β-agonist to alter fat and muscle deposition in steers. J. Anim. Sci. **59**: 1247–1255.

Saltiel, A. R. and Kahn, C. R. 2001. Insulin signaling and the regulation of glucose and lipid metabolism. Nature (Lond.) **414**: 799–806.

SAS Institute Inc. 2006. SAS user's guide: Statistics. Version 9.1.3. SAS Institute Inc., Cary, NC.

Scramlin, S. M., Platter, W. J., Gomez, R. A., Choat, W. T. F., McKeith, K. and Killefer, J. 2010. Comparative effects of ractopamine hydrochloride and zilpaterol hydrochloride on growth performance, carcass traits, and *longissimus* tenderness of finishing steers. J. Anim. Sci. **88**: 1823–1829.

Schroeder, A. L., Polser, D. M., Laudert, S. B. and Vogel, G. J. 2003. The effect of Optaflexx on growth performance and carcass traits of steers. Optaflexx Exchange No. 1. Elanco Anim. Health, Greenfield, IN.

Shook, J. N., VanOverbeke, D. L., Kinman, L. A., Krehbiel, C. R., Holland, B. P., Streeter, M. N., Yates, D. A. and Hilton, G. G. 2009. Effects of zilpaterol hydrochloride and zilpaterol hydrochloride withdrawal time on beef carcass cutability, composition and tenderness. J. Anim. Sci. **87**: 3677–3685.

Smith, O. B. and Akinbamizo, O. O. 2000. Micronutrients and reproduction in farm animals. Anim. Reprod. Sci. **60–61**: 549–560.

Spears, J. W. and Kegley, E. B. 2002. Effect of zinc source (zinc oxide vs zinc proteinate) and level on performance, carcass characteristics, and immune response of growing and finishing steers. J. Anim. Sci. **80**: 2747–2752.

Tang, X. and Shay, N. F. 2001. Zinc has an insulin-like effect on glucose transport mediated by phosphoinositol-3-kinase and akt in 3T3-L1 fibroblasts and adipocytes. J. Nutr. **131**: 1414–1420.

United States Department of Agriculture. 1997. United States standards for grades of carcass beef. Agric. Marketing Service, USDA, Washington, DC.

United States Department of Agriculture. 2006. Instrument grading systems for beef carcasses. [Online] Available: http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELDEV3097857 [2014 Mar. 18].

United States Department of Agriculture. 2011. Method for grid assessment of beef carcass rib eye area. [Online] Available: http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5090712 [2014 Mar. 18].

Van Soest, P. J., Robertson, J. B. and Lewis, B. A. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. **74**: 3583–3597.

Vardatsikos, G., Nihar, N. P. and Ashok, K. S. 2013. Insulin-mimetic and anti-diabetic effects of zinc. J. Inorg. Biochem. **120**: 8–17.

Vasconcelos, J. T. and Galyean, M. L. 2007. Nutritional recommendations of feedlot consulting nutritionist: The 2007 Texas Tech University survey. J. Anim. Sci. **85**: 2772–2781.

Vierboom, M., Engle, T. E. and Kimberling, C. V. 2003. Effects of gestational status on apparent absorption and retention of copper and zinc in mature Angus cows and Suffolk ewes. Asian Austr. J. Anim. Sci. **16**: 515–518.

Winterholler, S. J., Parson, G. L., Reinhardt, C. D., Hutcheson, J. P., Nichols, W. T., Yates, D. A., Swingle, R. S. and Johnson, B. J. 2007. Response to ractopamine-hydrogen chloride is similar in yearling steers across days on feed. J. Anim. Sci. **85**: 413–419.