Archiv Tierzucht 52 (2009) 1, 28-39, ISSN 0003-9438

Relationships among dual-energy X-ray absorptiometry, bioelectrical impedance and ultrasound measurements of body composition of swine

ALVA D. MITCHELL[1] and ARMIN M. SCHOLZ[2]

[1]Agricultural Research Service, U.S. Department of Agriculture, Beltsville, MD, USA, [2]Livestock Center, University Munich, Oberschleißheim, Germany

Abstract

In three separate studies (156 pigs total), dual-energy X-ray absorptiometry (DXA), bioelectrical impedance (BIA) and ultrasound were compared as methods for measuring live body composition of pigs at 60 and 100-110 kg BWt. DXA measured total body fat and lean content, BIA measurements of resistance (Rs) and reactance (Xc) were used to calculate total body lean mass and ultrasound measurements of backfat (BF) depth and *longissimus* muscle area (LMA) were used to calculate total carcass lean mass. Following the 100-110 kg measurements, the pigs were slaughtered and the half-carcass analyzed chemically for fat and water content. At 110 kg both DXA and ultrasound measurements were significantly correlated with the percentages of carcass fat and water, although correlations were higher for DXA. The correlations between DXA and BF measurements were higher at 110 kg than at 60 kg, whereas they were lower for DXA and LMA. For pigs measured at 100 kg there were high correlations between the DXA values and the BIA estimates for both percentage of fat-free lean mass (FFM %) and FFM kg. Furthermore, the correlations between the BIA estimates of FFM and carcass fat and water content were similar to those for DXA and the same carcass values. This study also provided a side-by-side comparison of the BIA and ultrasound lean measurements relative to DXA and carcass composition. The BIA lean measurement correlated more highly with both DXA and carcass composition than did the ultrasound lean measurement.

Keywords: dual energy X-ray absorptiometry, bioelectrical impedance, ultrasound, swine, body composition

Zusammenfassung

Beziehungen zwischen Dualenergie-Röntgenabsorptiometrie, bioelektrischer Impedanz und Ultraschall zur Messung der Körperzusammensetzung beim Schwein

In drei separaten Studien wurden die Dualenergie-Röntgenabsorptiometrie (DXA), bioelektrischer Impedanz (BIA) und Ultraschall als Methoden zur Messung der Körperzusammensetzung anhand von insgesamt 156 Schweinen bei Lebendmassen von 60 und 100-110 kg verglichen. DXA lieferte Daten zum Gesamtkörperfett- und –magerweichgewebegehalt. Die BIA-Messwerte zum Ohmschen Widerstand (resistance, Rs) und induktiven Blindwiderstand (reactance, Xc) dienten der Berechnung der Gesamtkörpermagermasse, während die Ultraschallmesswerte für Rückenspeckdicke (BF) und

Kotelettfläche (LMA) zur Berechnung der Schlachtkörperfleischmasse genutzt wurden. Im Anschluss an die 100-110 kg Messungen wurden die Schweine geschlachtet und jeweils eine Schlachtkörperhälfte chemisch auf Fett- und Wassergehalt analysiert. Bei 110 kg waren sowohl die DXA- als auch die Ultraschallmesswerte signifikant mit dem prozentualen Schlachtkörperfett und -wasser korreliert, wobei die Korrelationen mit den DXA-Messwerten höher ausfielen. Die Korrelationen zwischen DXA- und Ultraschall-Rückenspeckmesswerten waren bei 110 kg höher als bei 60 kg; gekoppelt mit generell niedrigeren Korrelationen zwischen DXA- und Ultraschall-Kotelettmesswerten. Bei 100-kg-Schweinen gab es hohe Korrelationen zwischen den DXA-Werten und den BIA-Schätzwerten sowohl für die prozentuale fettfreie Masse (FFM %) als auch für FFM (kg). Die Korrelationen zwischen den BIA-Schätzwerten für FFM und dem Schlachtkörperfett- bzw. -wassergehalt unterschieden sich nicht von denen zwischen DXA und den Schlachtkörperwerten. Diese Studie ermöglicht außerdem einen direkten Vergleich von BIA- und Ultraschall-Magergewebemessungen relativ zur DXA- und Schlachtkörperzusammensetzung. In beiden Fällen lagen die Korrelationskoeffizienten für BIA höher als für die Ultraschallmesswerte.

Schlüsselwörter: Dualenergie-Röntgenabsorptiometrie, bioelektrische Impedanz, Ultraschall, Schwein, Körperzusammensetzung

Introduction

In recent years, a variety of approaches has been used to probe the animal in an attempt to gather information on in vivo body composition. These include the use of ultrasound, x-rays, gamma rays, near-infrared rays, nuclear magnetic resonance, electrical impedance, electromagnetic conductivity, and neutron activation. Techniques that utilize these approaches include dual-energy X-ray absorptiometry (DXA), bioelectrical impedance (BIA) and real-time ultrasound (US). The purpose of the present study is to provide a side-by-side comparison of these three techniques for measuring body composition of swine.

The DXA technique has been used to measure the body composition of live pigs (MITCHELL & SCHOLZ 1997, 2008, MITCHELL *et al.* 2002, SCHOLZ & FÖRSTER 2006, BEE *et al.* 2007) and pig carcasses (MITCHELL *et al.* 1998). The total body DXA scan provides measurements of total body fat, lean, bone mineral and bone mineral density. The DXA measurement of fat content of the live pig is highly correlated to the fat content (r=0.915 for percentage fat and 0.989 for fat weight) of the chemically analyzed carcass MITCHELL *et al.* 1996).

In limited studies, BIA has been used to predict the fat-free mass of live pigs and carcasses (SWANTEK *et al.* 1992) and the Boston butt portion of pork carcasses (MARCHELLO & SLANGER 1992). It has also been tested for measuring the fat-free mass of lambs and lamb carcasses (BERG & MARCHELLO 1994, BERG *et al.* 1996, 1997, HEGARTY 1998, SÜSS *et al.* 2001), and the composition of steer carcasses (VELAZCO *et al.* 1999). The BIA procedure consists of placing two sets of electrodes at defined locations on either the live pig or carcass. Once the electrodes are in place, the impedance readings (Rs and Xc) are taken. The study by SWANTEK *et al.* (1992) reported correlations of –0.56 and –0.63 between Rs and fat-free mass (FFM) and 0.64 and 0.70 between Rs and percentage fat for live and carcass measurements, respectively. The correlations were not as good for Xc (−0.11, −0.08, −0.11, and 0.17, respectively).

Historically, ultrasound has become the most common in vivo technology in swine body composition assessment (KLIESCH *et al.* 1957, STOUFFER *et al.* 1961, HORST 1971). Several studies have reported equations for the prediction of percentage lean or lean cuts utilizing ultrasound measurements of live pigs (TERRY *et al.* 1989, GRESHAM *et al.* 1992, CISNEROS *et al.* 1996, MÜLLER & POLTEN 2004). These equations based on transverse or longitudinal scans include anywhere from one to four fat depth readings from a variety of locations, most include either LM depth or area and some include body weight. The reported accuracy of these equations ranges from an R^2 of 0.36 and residual standard deviation (RSD) of 3.17 to an R^2 of 0.83 and RSD of 1.67.

The advantages and disadvantages of these and other methods for measuring the body composition of swine have been discussed previously (MITCHELL & SCHOLZ 2004). In studies of human body composition there are numerous reports where techniques have been cross-validated, especially with DXA and BIA, however with swine there has been no prior study that provides a side-by-side comparison of the techniques evaluated here-in.

Material and methods

A total of 156 pigs were used in three separate studies. The pigs were of mixed genetic background and on standard diets. In the first study 99 pigs were measured by DXA and ultrasound at 60 kg; of those, 93 were measured again at 110 kg. Following the measurements at 110 kg, the pigs were euthanized and the half-carcass analyzed chemically for fat and water content. The second study consisted of 33 pigs; each pig was measured by DXA and BIA at 60 kg, 18 of the pigs were fed at maintenance for eight weeks then measured again (a total of 51 measurements at 60 kg) and finally all pigs were measured at 100 kg. After the measurement at 100 kg, the pigs were euthanized and the half-carcass analyzed chemically for fat and water content. In addition, for each of the half-carcasses the area of the *longissimus* muscle (LM) was determined at the level of the 10th rib and fat thickness (P2BF) over the LM was measured at 65 mm from the midline. The third study consisted of 24 pigs; each pig was measured by DXA, ultrasound, and BIA at 60 kg, 14 of the pigs were fed at maintenance for eight weeks then measured again (a total of 38 measurements at 60 kg) and finally all pigs were measured at 100 kg. After the measurement at 100 kg, the pigs were euthanized and the half-carcass analyzed chemically for fat and water content.

DXA measurements

Each pig was scanned by DXA for body composition analysis as described by Mitchell *et al.* (1996). The DXA scans were performed using either the Lunar (GE-Lunar, Madison, WI) DPXL (1st study) or the Lunar Prodigy (2nd and 3rd studies) densitometer. Pigs were fasted overnight and then anesthetized (500 mg ketamine, 80 mg tiletamine, 80 mg zolazepam and 333 mg xylazine per 100 kg body weight, i.m.) to prevent movement during the scanning procedure. The DXA scans provided measurements of total body fat, lean, and bone mineral content (BMC). Each pig was placed on the instrument in a prone position and a total body scan was performed.

Ultrasound measurements

Following the DXA scan, while the pig was still anesthetized and lying in the prone position, ultrasound images were obtained using an Aloka Model SSD-500V. The hair was clipped and the transducer, fitted to a stand-off guide, was placed at the level of the 10th rib. The ultrasound image was used to measure thickness of the backfat (BF, cm) layer and area of the *longissimus* muscle (LMA, cm^2). Fat-free lean mass was calculated using the NPPC (1999) formula:

$$\text{US-FMM}=[0.9983-2.6425\cdot \text{BF}+0.3488\cdot \text{LMA}+0.3312\cdot \text{LWt}] \quad (1)$$

BIA measurements

Following the DXA scan, also while the pig was still anesthetized and lying in the prone position, measurements of resistance (Rs, Ω) and reactance (Xc, Ω) were made using a four-terminal plethysmograph (BIA; Model BIA-101, RJL Systems, Inc.). The four needle electrodes were implanted as described by SWANTEK *et al.* 1992). Fat-free lean mass (FFM, kg) was calculated using Rs, Xc, live weight (LWt, kg), and body length (L, cm), based on the model reported by SWANTEK *et al.* (1992):

$$\text{BIA-FMM}=0.486\cdot \text{LWt}-0.881\cdot \text{Rs}+0.480\cdot \text{L}+0.860\cdot \text{Xc}+7.959 \quad (2)$$

Chemical analysis

At slaughter, the head and viscera were removed, and the carcass was split at the midline. The hair and feet remained on the carcass. The right half-carcass was analyzed chemically for lipid (FOLCH *et al.* 1957) and water (lyophilization) content.

Statistical analysis

Data were analyzed using Statgraphics Plus (Ver. 5.1) multi-variable analysis which generated the mean and standard deviation for each variable and the Pearson product moment correlation for each pair of variables. Statistical significance of the correlation coefficients was based on *P*-values.

Results

The body weight and composition measurements of the pigs in the three studies are shown in tables 1-3. Within weight groups, there was close agreement for the DXA results among the three studies. The DXA measurements for percentage of body fat at 60 kg were 11.8, 12.1, and 11.7 and at 100-110 kg they were 19.0, 18.4, and 17.5 for the 1st, 2nd, and 3rd studies, respectively. Likewise, for pigs in the 100-110 kg group, there was close agreement based on chemical analysis of the half-carcass. The percentages of fat in the half-carcass for the 1st, 2nd, and 3rd studies were 25.9, 24.6, and 25.1, respectively. In addition to the DXA measurements, results of the ultrasound measurements of BF and LMA are shown in Tables 1 and 3 and results of the BIA measurements are shown in Tables 2 and 3.

Table 1
Composition measurements of pigs at 60 and 100 kg BW using DXA and ultrasound and chemical analysis of half-carcass of 100 kg pigs (1st study)

Körperzusammensetzung von Schweinen bei 60 und 100 kg Lebendmasse aus DXA bzw. Ultraschall und chemischer Analyse einer Schlachthälfte der 100-kg-Schweine (1. Studie)

Variable	60 kg Pigs (*n*=99)			110 kg Pigs (*n*=93)		
	Mean	SD	Range	Mean	SD	Range
Live wt, kg	60.3	2.18	55.2-69.2	110.4	2.01	105.0-114.9
DXA fat, %	11.8	4.08	4.3-22.6	19.0	5.67	10.3- 36.2
DXA fat, kg	6.9	2.38	2.4-12.4	20.6	6.16	11.2- 38.3
DXA lean, %	85.7	4.15	74.5-93.0	79.0	5.69	61.7- 87.5
DXA lean, kg	50.7	3.36	40.9-61.8	85.6	6.23	65.2- 95.8
LMA, cm^2	22.1	3.06	16.9-29.5	36.7	5.31	23.5- 48.5
BF, cm	1.7	0.34	1.0- 2.7	2.6	0.61	1.1- 4.3
LMA/BF	13.9	3.84	6.6-24.0	14.8	4.65	7.3- 30.0
US-FFM, %	40.2	2.56	33.3-46.4	39.3	2.56	33.7- 44.7
US-FFM, kg	24.3	1.97	18.8-30.7	43.4	2.80	36.1- 49.7
Carcass fat, %				25.9	4.62	16.8- 39.8
Carcass H_2O, %				53.0	4.09	41.2- 60.7

LMA *longissimus* muscle area, BF P2 backfat depth, US-FFM fat-free lean mass calculated using the NPPC (1999) formula

Table 2
Composition measurements of pigs at 60 and 100 kg BW using DXA and BIA and chemical analysis and physical measurements of half-carcass of 100 kg pigs (2nd study)

Körperzusammensetzung von Schweinen bei 60 und 100 kg Lebendmasse aus DXA bzw. BIA und chemischer bzw. planimetrischer Analyse einer Schlachthälfte der 100-kg-Schweine (2. Studie)

Variable	60 kg Pigs (n=51)			100 kg Pigs (n=33)		
	Mean	SD	Range	Mean	SD	Range
Live wt, kg	60.7	2.73	54.9-68.0	100.3	2.60	94.5-107.9
DXA fat, %	12.1	3.02	4.9-19.7	18.4	3.75	9.9-24.8
DXA fat, kg	7.4	1.92	3.0-12.1	18.4	3.73	9.9-24.7
DXA lean, %	85.6	2.93	77.7-92.1	79.6	3.77	73.3-87.9
DXA lean, kg	51.9	2.67	46.2-58.6	79.8	4.51	70.5-90.3
Rs, Ω	39.2	2.93	34.3-45.6	39.4	3.31	34.1-46.3
Xc, Ω	7.0	1.10	5.2- 9.9	6.4	0.57	5.0- 7.4
BIA-FFM, kg	37.2	2.94	31.8-43.7	62.9	3.67	53.6-69.9
BIA-FFM, %	61.2	3.25	54.5-69.1	62.7	2.96	55.9-67.8
Carcass LMA, cm^2				32.2	6.81	20.6-45.8
Carcass BF, cm				1.9	0.47	1.0- 3.0
Carcass fat, %				24.6	4.54	14.3-34.4
Carcass H_2O, %				53.1	3.38	46.4-60.1

Rs BIA resistance measurement, Xc BIA reactance measurement, BIA-FFM fat free lean mass calculated using the BIA model of Swantek (1992), LMA *longissimus* muscle area, BF P2 backfat depth, SD standard deviation

Correlation coefficients for body composition measurements using DXA, ultrasound and BIA are shown in tables 4-6. In the 1st study, there were significant correlations for all DXA and ultrasound measurements at both 60 kg (Table 4a) and at 110 kg (Table 4b). At 110 kg both DXA and ultrasound measurements were significantly correlated with the percentages of carcass fat and water. At both 60 and 110 the lowest correlations were for LMA. The correlations between DXA and BF measurements were higher at 110 kg than at 60 kg, whereas they were lower for DXA and LMA.

Table 3
Composition measurements of pigs at 60 and 100 kg BW using DXA, BIA, ultrasound and chemical analysis as well physical measurements of half-carcass of 100 kg pigs (3rd study)
Körperzusammensetzung von Schweinen bei 60 und 100 kg Lebendmasse aus DXA, BIA bzw. Ultraschall und chemischer bzw. planimetrischer Analyse einer Schlachthälfte der 100-kg-Schweine (3. Studie)

Variable	60 kg Pigs (n=38)			100 kg Pigs (n=24)		
	Mean	SD	Range	Mean	SD	Range
Live wt, kg	62.2	2.38	57.7-66.2	101.6	2.88	97.7-107.0
DXA fat, %	11.7	3.67	6.6-20.6	17.5	4.05	11.3-26.2
DXA fat, kg	7.4	2.35	4.0-13.2	18.1	4.19	11.9-27.5
DXA lean, %	86.2	3.66	77.4-91.2	80.4	4.08	71.8-86.8
DXA lean, kg	54.9	3.72	49.2-63.1	83.4	5.01	75.3-93.4
Rs, Ω	38.8	3.21	32.9-46.7	39.8	2.90	35.5-47.0
Xc, Ω	5.8	1.45	3.1- 9.0	5.7	0.62	4.5-6.8
BIA-FFM, kg	38.5	3.63	31.8-46.0	63.8	3.36	56.1-70.8
BIA-FFM, %	61.9	4.78	51.6-69.9	62.8	3.18	56.9-67.4
LMA, cm^2	23.0	2.47	17.6-27.1	33.2	3.10	27.2-37.9
BF, cm	1.5	0.42	0.7- 2.4	2.3	0.47	1.4-3.1
LMA/BF	16.7	6.88	8.0-35.9	15.0	3.85	9.6-24.8
US-FFM, %	41.1	2.78	35.4-46.2	39.5	1.75	36.1-42.2
US-FFM, kg	25.6	2.18	20.9-29.7	40.1	2.05	37.4-45.1
Carcass fat, %				25.1	3.94	19.7-33.1
Carcass H_2O, %				54.0	3.59	46.6-58.7

Table 4a
Correlation matrix for DXA and ultrasound measurements of body composition of 60 kg pigs (1st study)
Korrelationsmatrix für DXA- und Ultraschallmesswerte der Körperzusammensetzung von 60-kg-Schweinen (1. Studie)

Variable	DXA fat, %	DXA fat, kg	DXA lean, %	DXA lean, kg	LMA, cm^2	BF, cm	LMA/BF	US-FFM, %
DXA fat (kg)	0.99***							
DXA lean (%)	−0.99***	−0.99***						
DXA lean (kg)	−0.83***	−0.76***	0.83***					
LMA (cm^2)	−0.48***	−0.44***	0.48***	0.55***				
BF (cm)	0.68***	0.66***	−0.67***	−0.61***	−0.31**			
LMA/BF	−0.70***	−0.67***	0.69***	0.68***	0.69***	−0.87***		
US-FFM (%)	−0.64***	−0.57***	0.64***	0.83***	0.82***	−0.69***	0.88***	
US-FFM (kg)	−0.71***	−0.68***	0.70***	0.66***	0.83***	−0.77***	0.94***	0.90***

Table 4b
Correlation matrix for DXA and ultrasound measurements of body composition of 110 kg pigs (1st study)
Korrelationsmatrix für DXA- und Ultraschallmesswerte der Körperzusammensetzung von 110-kg-Schweinen (1. Studie)

Variable	DXA fat, %	DXA fat, g	DXA lean, %	DXA lean, g	LMA, cm^2	BF, cm	LMA/BF	US-FFM, %	US-FFM, kg	Carc. fat, %
DXA fat, kg	0.99***									
DXA lean, %	−0.99***	−0.99***								
DXA lean, kg	−0.97***	−0.95***	0.97***							
LMA, cm^2	−0.35***	−0.35***	0.35***	0.34***						
BF, cm	0.82***	0.82***	−0.81***	−0.75***	−0.33**					
LMA/BF	−0.72***	−0.73***	0.72***	0.66***	0.64***	−0.89***				
US-FFM, %	−0.70***	−0.71***	0.70***	0.64***	0.83***	−0.79***	0.93***			
US-FFM, kg	−0.67***	−0.66***	0.67***	0.67***	0.85***	−0.73***	0.88***	0.96***		
Carcass fat, %	0.85***	0.83***	−0.85***	−0.85***	−0.45***	0.70***	−0.69***	−0.69***	−0.70***	
Carcass H_2O, %	−0.89***	−0.88***	0.89***	0.88***	0.38***	−0.73***	0.68***	0.66***	0.66***	−0.91***

Rs BIA resistance measurement, Xc BIA reactance measurement, BIA-FFM fat free lean mass calculated using the BIA model of Swantek (1992), LMA *longissimus* muscle area, BF P2 backfat depth, US-FFM fat-free lean mass calculated using the NPPC (1999) formula, SD standard deviation, *$P<0.05$, **$P<0.01$, ***$P<0.001$

In the 2nd study, at 60 kg (Table 5a) DXA measurements (with the exception of DXA lean kg) were significantly correlated with BIA reactance (Xc), but not resistance (Rs). However, at 110 kg (Table 5b) the DXA measurements were significantly correlated with Rs, but not Xc. At both weights the DXA measurements were significantly correlated with the BIA estimate of fat free lean%, although the correlations were higher at 110 kg. At 110 kg both DXA and BIA measurements were significantly correlated with the percentages of carcass fat and water.

Table 5a
Correlation matrix for DXA and BIA measurements of body composition of 60 kg pigs (2nd study)
Korrelationsmatrix für DXA- und BIA-Messwerte der Körperzusammensetzung von 60-kg-Schweinen (2. Studie)

Variable	DXA fat, %	DXA fat, kg	DXA lean, %	DXA lean, kg	Rs	Xc	BIA-FFM, kg
DXA fat, kg	0.98***						
DXA lean, %	−0.99***	−0.9***					
DXA lean, kg	−0.48***	−0.34*	0.49***				
Rs	−0.03	−0.10	−0.00	−0.46***			
Xc	−0.56***	−0.60***	0.54***	−0.00	0.58***		
BIA-FFM, kg	−0.35*	−0.21	0.35*	0.92***	−0.65***	−0.05	
BIA-FFM, %	−0.68***	−0.61***	0.69***	0.72***	−0.55***	0.25	0.84***

Table 5b
Correlation matrix for DXA, BIA, and carcass measurements of body composition of 100 kg pigs (2nd study)
Korrelationsmatrix für DXA-, BIA- und Schlachtkörper-Messwerte der Körperzusammensetzung von 100-kg-Schweinen (2. Studie)

Variable	DXA fat, %	DXA fat, kg	DXA lean, %	DXA lean, kg	Rs	Xc	BIA-FFM, kg	BIA-FFM, %	Carcass BF, cm	Carcass LMA, cm^2	Carcass fat, %
DXA fat, kg	0.99***										
DXA lean, %	−0.89***	−0.83***									
DXA lean, kg	−0.99***	−0.99***	0.88***								
Rs	0.72***	0.69***	−0.72***	−0.75***							
Xc	−0.16	−0.16	0.16	0.11	−0.17						
BIA-FFM, kg	−0.71***	−0.64***	0.70***	0.87***	−0.88***	0.26					
BIA-FFM, %	−0.82***	−0.80***	0.81***	0.78***	−0.92***	0.34	0.90***				
Carcass BF, cm	0.47**	0.47**	−0.45*	−0.38**	0.33	−0.00	−0.33	−0.41*			
Carcass LMA, cm^2	−0.21	−0.21	0.21	0.20	−0.44**	0.28	0.31	0.36*	−0.13		
Carcass fat, %	0.71***	0.71***	−0.71***	−0.64***	0.61***	−0.35*	−0.61***	−0.70***	0.52**	−0.43*	
Carcass H_2O, %	−0.67***	−0.67***	0.66***	0.60***	−0.58***	0.35*	0.59***	0.68***	−0.51**	0.45**	−0.92***

Rs BIA resistance measurement, Xc BIA reactance measurement, BIA-FFM fat free lean mass calculated using the BIA model of Swantek (1992), LMA *Longissimus* muscle area, BF P2 backfat depth, * $P<0.05$, ** $P<0.01$, *** $P<0.001$

In the 3rd study, at 60 kg (Table 6a) there were significant correlations among the DXA, ultrasound, and BIA measurements, with exceptions for both Rs and Xc. At 110 kg (Table 6b) there were significant correlations among the DXA, ultrasound, BIA, and carcass measurements, with the exception of both LMA and Xc.

Table 6a

Correlation matrix for DXA, BIA, and ultrasound measurements of body composition of 60 kg pigs (3rd study)

Korrelationsmatrix für DXA-, BIA- und Ultraschall-Messwerte der Körperzusammensetzung von 60-kg-Schweinen (3. Studie)

Variable	DXA fat, %	DXA fat, kg	DXA lean, %	DXA lean, kg	LMA, cm^2	BF, cm	LMA/BF	US-FFM, %	US-FFM, kg	Rs	Xc	BIA-FFM, kg
DXA fat, kg	0.99***											
DXA lean, %	−0.99***	−0.99***										
DXA lean, kg	−0.68***	−0.56***	0.68***									
LMA, cm^2	−0.58***	−0.52***	0.58***	0.67***								
BF, cm	0.75***	0.75***	−0.74***	−0.52***	−0.64***							
LMA/BF	−0.71***	−0.70***	0.70***	0.52***	0.72***	−0.93***						
US-FFM, %	−0.74***	−0.73***	0.73***	0.57***	0.85***	−0.94***	0.92***					
US-FFM, kg	−0.67***	−0.60***	0.67***	0.80***	0.90***	−0.81***	0.84***	0.90***				
Rs	0.61***	0.65***	−0.62***	−0.21	−0.29	0.27	−0.25	−0.32*	−0.25			
Xc	−0.32	−0.29	0.30	0.36*	0.46**	−0.64***	0.68***	0.61***	0.56***	0.32		
BIA-FFM, kg	−0.79***	−0.73***	0.79***	0.81***	0.75***	−0.64***	0.65***	0.71***	0.83***	−0.58***	0.31	
BIA-FFM, %	−0.87***	−0.87***	0.87***	0.61***	0.66***	−0.70***	0.68***	0.75***	0.69***	−0.72***	0.30	0.92***

Table 6b

Correlation matrix for DXA, BIA, ultrasound, and carcass measurements of body composition of 100 kg pigs (3rd study)

Korrelationsmatrix für DXA-, BIA-, Ultraschall- und Schlachtkörper-Messwerte der Körperzusammensetzung von 100-kg-Schweinen (3. Studie)

Variable	DXA fat, %	DXA fat, kg	DXA lean, %	DXA lean, kg	LMA, cm^2	BF, cm	LMA/BF	US-FFM, %	US-FFM, kg	Rs	Xc	BIA-FFM, kg	BIA-FFM, %	Carcass H_2O, %
DXA fat, kg	0.99***													
DXA lean, %	−0.99***	−0.99***												
DXA lean, kg	−0.88***	−0.81***	0.88***											
LMA, cm^2	−0.10	−0.08	0.09	0.19										
BF, cm	0.78***	0.78***	−0.78***	−0.70***	−0.18									
LMA/BF	−0.66***	−0.64***	0.65***	0.66***	0.51*	−0.91***								
US-FFM, %	−0.64***	−0.63**	0.62**	0.59**	0.70***	−0.82***	0.93***							
US-FFM, kg	−0.42*	−0.36	0.41*	0.60**	0.73***	−0.64***	0.84***	0.83***						
Rs	0.86***	0.83***	−0.86***	−0.85***	−0.32	0.76***	−0.74***	−0.72***	−0.64***					
Xc	−0.09	−0.15	0.07	−0.11	0.18	−0.37	0.37	0.41*	0.11	−0.05				
BIA-FFM, kg	−0.74***	−0.68***	0.73***	0.85***	0.28	−0.75***	0.74***	0.66***	0.77***	−0.86***	0.03			
BIA-FFM, %	−0.91***	−0.90***	0.91***	0.81***	0.17	−0.86***	0.75***	0.73***	0.53**	−0.90***	0.27	0.85***		
Carcass H2O, %	−0.88***	−0.87***	0.87***	0.78***	0.25	−0.79***	0.72***	0.71***	0.55**	−0.83***	0.13	0.80***	0.90***	
Carcass fat, %	0.88***	0.87***	−0.87***	0.75***	−0.28	0.82***	−0.74***	−0.74***	−0.57**	0.84***	−0.19	−0.80***	−0.91***	−0.95***

Rs BIA resistance measurement, Xc BIA reactance measurement, BIA-FFM Fat free lean mass calculated using the BIA model of Swantek (1992), LMA *Longissimus* muscle area, BF P2 backfat depth, US-FFM Fat-free lean mass calculated using the NPPC (1999) formula, * $P<0.05$, ** $P<0.01$, *** $P<0.001$

Discussion

The estimates of percentage of lean varied considerably, depending on the method of measurement. Based on averages for the three studies, for pigs at 60 kg the lean content measured by DXA was 85.8%, by BIA (BIA-FFM) 61.6% and by ultrasound (US-FFM) 40.65%. For pigs measured at 100 to 110 kg the lean content by DXA was 79.7%, by BIA 62.8%, and by ultrasound 39.4%. By chemical analysis, the average water content of the carcasses of pigs measured at 100 to 110 kg was 53.4%. Assuming a protein content of 16% (MITCHELL *et al.* 1998), this would translate to a lean content of 69% for the carcass. The reason for the discrepancies among these methods is that they each take a different approach for measuring »lean«. DXA, based on a three compartment model, measures total body fat and bone mineral content and the lean component includes »all other«. BIA is based on a two-compartment model consisting of fat mass and fat-free mass (FFM) as described by LUKASKI (1987). The formula (SWANTEK *et al.* 1992) for calculating FFM of pigs using BIA measurements was derived by subtracting the product of live body mass and the percentage of fat in the cold carcass from the live body mass. This calculation assumed that fat was distributed uniformly throughout the animal and was the same percentage found in non-carcass body parts as in the carcass. The formula for calculating carcass fat free lean (US-FFM) using live ultrasound measurements of BF depth and LM area (NPPC 1999) is based on total lipid-free (chloroform/methanol extracted, FOLCH *et al.* 1957) lean that was dissected from the carcass.

The DXA measurement of total body lean can be adjusted for bone content rather than BMC (PURSEL *et al.* 2004) by assuming a 24.14% ash content for pork bones (FIELD *et al.* 1974). Furthermore, it has been demonstrated that there is a close relationship between live DXA measured lean and carcass lean (SCHOLZ *et al.* 2007, SUSTER *et al*, 2003), indicating that the live DXA lean measurement can be used to predict carcass lean. Also, SWANTEK *et al.* (1992) reported an equation for their BIA measurements that adjusted for live weight to offset discrepancies between carcass weights and live weights using average head and viscera weights and estimated blood loss.

It should be noted that with both DXA and ultrasound measurements, as expected – with an increase in fat percentage, the percentage of lean decreased from the 60 kg to the 100-110 kg measurements, whereas with BIA there was an increase in the percentage of lean (fat free mass) in both studies (Tables 2 and 3). A later study by SWANTEK *et al.* (1999), using the same prediction equation as used here, reported high correlations between actual and BIA predicted FFM, but that BIA underestimated FFM in pigs ranging from 50 to 130 kg. The degree of underestimation was greater with smaller pigs, for example, for barrows at 50 kg BIA-FFM was underestimated by 16%, but only 3.4% at 130 kg and the percentage of BIA-FFM increased from 61.8 for 50 kg barrows to 64.7 for 90 kg barrows. This could explain the increase in percentage in BIA-FFM for 100 kg pigs compared to 60 kg pigs that was observed in the present study and suggests the need for separate prediction equations based on body size.

In previous studies DXA measurements of total body fat and lean were found to correlate with the percentages of carcass fat and lean with R^2 values ranging from 0.78 to 0.85

(SCHOLZ *et al.* 2007). The formula used in this study for calculating fat-free lean based on ultrasound measurements has a reported R^2 value of 0.777 (NPPC 1999). However, the use of ultrasound for assessing live animal composition is subject to a number of measurement errors (HOUGHTON and TURLINGTON 1992). For ultrasound measurements, the correlations between lean percentage and ultrasound fat depth readings range from −0.44 to −0.63 (ISLER & SWIGER 1968, ANDERSON & WAHLSTROM 1969). MERSMANN (1982) reported very low correlations between ultrasound LMA measurements and the percentages of either fat or nitrogen in the carcass. In the studies reported here where DXA was compared with ultrasound measurements (1st and 3rd studies, Tables 4 and 6) the DXA measurements were more highly correlated with BF than with LMA. The correlation between DXA and BF was higher for the 100-110 kg pigs than with the 60 kg pigs, whereas, the correlation between DXA and LMA was higher with the 60 kg pigs. Both DXA fat and BF measurements correlate negatively with lean measurements. The correlation between DXA measured percentage lean and the NPPC calculated percentage US-FFM (using ultrasound BF and LMA measurements) ranged from 0.41 to 0.73. In both studies the DXA measurements of body composition were more highly correlated with carcass fat and water content than were the measurements based on ultrasound readings. Similarly, in the 2nd study (Table 5b) there were higher correlations between DXA measurements and carcass fat and water content compared to the correlations between carcass BF and LMA measurements and carcass fat and water content. Likewise, SUSTER *et al.* (2003) reported that DXA values were more strongly related with chemically-determined carcass values than were carcass P2 BF measurements. In a study where DXA was used to measure the half-carcass, the DXA measure of fat percentage in the half-carcass correlated with average BF and P2 BF measurements with R^2 values of 0.64 and 0.42, respectively (MITCHELL *et al.* 1998).

Comparing DXA and BIA (tables 5a and 6a), for pigs measured at 60 kg there did not appear to be a consistent relationship between the DXA values and the BIA measurements of resistance (Rs), reactance (Xc), or the BIA estimate for kg of FFM. However, there were consistently high correlations between the DXA values and the BIA estimates for percentage of FFM. For pigs measured at 100 kg (Tables 5b and 6b) there were positive correlations between the BIA Rs values and both DXA fat (0.69 to 0.86) and carcass fat content (0.61 to 0.84). Conversely there were high negative correlations between BIA Rs values and both DXA lean (−0.72 to −0.86) and carcass water content (−0.58 to −0.83). Similarly, the study by SWANTEK *et al.* (1992) found moderately high correlations between the BIA Rs values and carcass fat (0.54 to 0.56) and carcass lean (−0.52 to −0.56), but low correlations between the BIA Xc values and both carcass fat (−0.11 to −0.22) and carcass lean (−0.11 to −0.14). For pigs measured at 100 kg there were high correlations between the DXA values and the BIA estimates for both FFM % and FFM kg; and the correlations between the BIA estimates of FFM and carcass fat and water content were similar to those for DXA and the carcass values. The 3rd study provided the only comparisons between BIA and ultrasound measurements (Table 6a and b). For pigs measured at 60 kg there was a higher correlation between BIA reactance (Xc) and ultrasound measurements compared to BIA resistance (Rs) and ultrasound. Whereas, as observed for BIA (Xc and Rs) and DXA in the 2nd study (Table 5a and b) the opposite was true for pigs measured at 100 kg. At both 60 and 100 kg there were high correlations between the BIA and ultrasound estimates of fat-free lean. This study also provided the only side-by-side comparison of the BIA and ultrasound lean measurements relative to DXA and carcass composition. In both cases, the correlation coefficients were higher for BIA compared to the ultrasound values.

In conclusion, these studies found higher correlations among the measurements with pigs at 100-110 kg compared to pigs at 60 kg. The exceptions to this were the ultrasound LMA measurement and the BIA Xc measurement. For measurements at 100-110 kg; with ultrasound, BF correlated more highly with other parameters than did LMA; and with BIA, Rs correlated more highly with other parameters than did Xc. Also at 100-110, DXA (fat and lean) and BIA-FFM correlated more highly with chemical analysis of the half-carcass than did ultrasound (US-FFM).

References

Anderson LM, Wahlstrom RC (1969) Ultrasonic prediction of swine carcass composition. J Anim Sci 28, 593-600

Bee G, Pursel VG, Mitchell AD, Maruyama K, Wells KD, Solomon MB, Wall RJ, Coleman ME, Schwartz RJ (2007) Carcass composition and skeletal muscle morphology of swine expressing an insulin-like growth factor-I transgene. Arch Tierz 50, 501-19

Berg EP, Marchello MJ (1994) Bioelectrical impedance analysis for the prediction of fat-free mass in lambs and lamb carcasses. J Anim Sci 72, 322-9

Berg EP, Neary MK, Forrrest JC, Thomas DL, Kauffman RG (1996) Assessment of lamb carcass composition from live animal measurement of bioelectrical impedance or ultrasonic tissue depths. J Anim Sci 74, 2672-8

Berg EP, Neary MK, Forrrest JC, Thomas DL, Kauffman RG (1997) Evaluation of electronic technology to assess lamb carcass composition. J Anim Sci 75, 2433-44

Cisneros F, Ellis M, Miller KD, Novakofski J, Wilson ER, Mckeith FK (1996) Comparison of transverse and longitudinal real-time ultrasound scans for prediction of lean cut yields and fat-free lean content of live pigs. J Anim Sci 74, 2566-76

Field RA, Riley ML, Mello FC, Corbridge MH, Kotula AW (1974) Bone composition in cattle pigs sheep and poultry. J Anim Sci 39, 493-9

Folch J, Lees M, Sloan-Stanley GH (1957) A simple method for the isolation and purification of total lipids from animal tissues. J Biol Chem 226, 497-509

Gresham JD, McPeake SR, Bernard JK, Henderson HH (1992) Commercial adaptation of ultrasonography to predict pork carcass composition from live animals and carcass measurements. J Anim Sci 70, 631-9

Hegarty RS, McPhee JJ, Oddy VH, Thomas BJ BJ, Ward LC (1998) Prediction of the chemical composition of lamb carcasses from multi-frequency impedance data. Br J Nutr 79, 169-76

Horst P (1971) First results concerning the application of the Vidoson cross-section photo equipments in pigs. Züchtungsk 43, 208-18 [in German]

Houghton PL, Turlington LM: Application of ultrasound for feeding and finishing animals: A review. J Anim Sci 70, 930-41

Isler GA, Swiger LA (1968) Ultrasonic prediction of lean cut percent in swine. J Anim Sci 27, 377-82

Kliesch J, Neuhaus U, Silber E, Kostzewske H (1957) Studies of measurement of fat depth of live animals by means of ultrasound. J Anim Breed Genet 70, 29-32 [in German]

Lukaski HC (1987) Methods for the assessment of human body composition: traditional and new. Am J Clin Nutr 46, 537-56

Marchello MJ, Slanger WD (1992) Use of bioelectrical impedance to predict leanness of boston butts. J Anim Sci 70, 3443-50

Mersmann HJ (1982) Ultrasonic determination of backfat depth and loin area in swine. J Anim Sci 54, 268-75

Mitchell AD, Scholz AM (1997) Dual-energy x-ray absorptiometry (DXA) analysis of growth and body composition of pigs of different ryanodine receptor genotypes. Arch Tierz 40, 11-21

Mitchell AD, Scholz A, Pursel V (2002) Prediction of the body composition of pigs based on cross-sectional region analysis of dual energy X-ray absorptiometry (DXA) scans. Arch Tierz 45, 535-45

Mitchell AD, Scholz AM (2008) Efficiency of energy and protein deposition in swine measured by dual energy X-ray absorptiometry (DXA). Arch Tierz 51, 159-171

Mitchell AD, Scholz AM (2004) Body Composition: Indirect Measurements. In: Pond W, Bell A (Eds) Encyclopedia of Animal Science. Marcel Dekker Inc NY, 166-9

Mitchell AD, Scholz AM, Pursel VG, Evock-Clover CM (1998) Composition analysis of pork carcasses by dual-energy X-ray absorptiometry. J Anim Sci 76, 2104-14

Müller S, Polten S (2004) Comparative investigations for ultrasonic fat thickness measurements of pigs at the performance testing. Arch Tierz 47, 249-63 [in German]

NPPC (1999) Fat-free lean prediction equations. National Pork Producers Council. Des Moines Iowa USA

Pursel VG, Mitchell AD, Bee G, Elsasser TH, McMurtry JP, Wall RJ, Coleman ME, Schwartz RJ (2004) Growth and tissue accretion rates of swine expressing an insulin-like growth factor I transgene. Anim Biotech 15, 33-45

Scholz AM, Förster M (2006) Accuracy of dual energy X-ray absorptiometry (DXA) for the determination of the body composition of pigs *in vivo*. Arch Tierz 49, 462-76 [in German]

Scholz AM, Mitchell AD, Förster M, Pursel VG (2007) Two-site evaluation of the relation between *in vivo* and carcass dual energy x-ray absorptiometry (DXA) in pigs. Livest Sci 110, 1-11

Stouffer JR, Wallentine MV, Wellington GH, Diekmann A (1961) Development and application of ultrasonic methods for measuring fat thickness and rib-eye area in cattle and hogs. J Anim Sci 20, 759-67

Swantek PM, Crenshaw JD, Marchello MJ, Lukaski HC (1992) Bioelectrical impedance: A nondestructive method to determine fat-free mass of live swine and pork carcasses. J Anim Sci 70, 169-77

Swantek PM, Marchello MJ, Tilton JE, Crenshaw JD (1999) Prediction of fat-free mass of pigs from 50 to 130 kilograms live weight. J Anim Sci 77, 893-7

Suster D, Leury BJ, Ostrowska E, Butler KL, Kerton DJ, Wark JD, Dunshea FR (2003) Accuracy of dual energy x-ray absorptiometry (DXA) weight and P2 back fat to predict whole body and carcass composition in pigs within and across experiments. Livest Prod Sci 84, 231-42

Süß R, Altmann M, Pliquett U, von Lengerken G (2001) Practicability and limits of carcass composition assessment by the use of impedance spectroscopy. Arch Tierz 44 SI, 361-9

Terry CA, Savell JW, Recio HA, Cross HR (1989) Using ultrasound technology to predict pork carcass composition. J Anim Sci 67, 1279-84

Velazco J, Morril JL, Grunewald KK (1999) Utilization of bioelectrical impedance to predict carcass composition of Holstein steers at 3, 6, 9 and 12 months of age. J Anim Sci 77, 131-6

Received 2 October 2008, accepted 27 November 2008.

Corresponding author:

Dr. ALVA D. MITCHELL
email: alva.mitchell@ars.usda.gov

Animal Biosciences and Biotechnology Laboratory, USDA-Agricultural Research Service, Animal Biosciences and Biotechnology Laboratory, Beltsville, MD 20705, USA