UNDERSTANDING THE ROLE OF UTERINE BLOOD FLOW ON OFFSPRING DEVELOPMENT AND MEAT QUALITY IN SWINE

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Piglets that are born with low viability have increased mortality during early life, result in increased labor by personnel and potential animal welfare concerns. Producers focused on improving ovulation rates with the outcome of increased number of piglets with the average of piglets born increasing from 8.0 pigs/litter/sow to 10.3 pigs/litter/sow (NASS, 2016). This may not be advantageous, as number of piglets born per litter increased the weight of each piglet decreased. It is hypothesized this is due to decreased uterine blood flow available per piglet in larger litters, resulting in lower viability piglets at birth. Two studies with the intent of improving uterine blood flow will be discussed. The first study will investigate how pharmaceuticals could enhance uterine blood flow in the gilt. The second study will discuss the postnatal outcome of offspring, who experienced greater umbilical blood flows, born from dams that were exercised during gestation.

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CHAPTER 1. LITERATURE REVIEW

Introduction

As litter size continues to increase, there is an increase in the number of low viability piglets born (Rutherford et al., 2013). Low viability pigs are quite costly to the US swine industry as they contribute to most deaths due to crushing, but also are often euthanized during the first few days of life due to their lack of thriftiness (Weary et al., 1996; Bauer et al., 1998; Edwards, 2002). Currently, the most utilized method of euthanasia for piglets less than three days of age is manually applied blunt force trauma to the skull (AVMA, 2013). When performed correctly, this method meets the definition of euthanasia, namely causing minimal distress with rapid loss of consciousness leading to death (AVMA, 2013). Piglets that this practice is used on are often runt piglets. Runt pigs are considered to be less than 0.8 kg of birth weight (Foxcroft et al., 2009). In many cases, the small intestine, liver, and skeletal muscle of runt pigs are disproportionately smaller than those of the largest littermates at birth (Widdowson, 1971). These underdeveloped systems lead to runt piglets having a low chance of survival to weaning or generating viable economic returns to producers. In today's commercial production systems, litter size is an important component of production and profitability. In past years the stance has been "more is better" with many producers selecting dams based on litter size or ovulation rates. Currently litter sizes of sows in United States production systems from December to February 2016 was 10.30 pigs/litter/sow (**Figure 1.1.**).

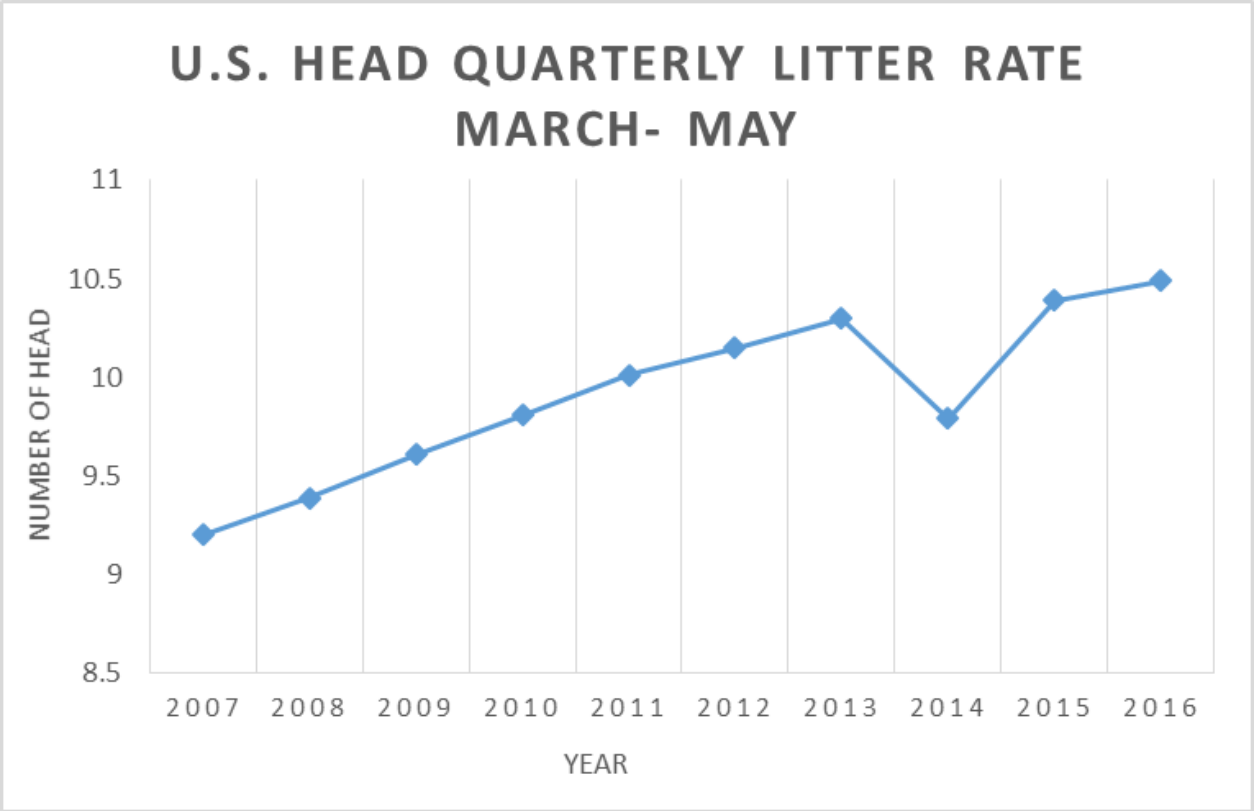

Figure 1.1. USDA National Agricultural Statistics Service Pigs per litter from March to May, 2007 to 2016. (Modified from USDA NASS, 2016).

Litter size has been trending upwards over the past several decades from previous numbers of 8 pigs/litter/sow (NASS, 2016). This increase in litter size is not due to a decrease in piglet mortality as the current preweaning piglet mortality rate is 15.4% (PigChamp, 2016) with the greatest contributor to piglet mortality being crushing of weaker piglets within the first day of life. This increase in mortality may be attributed to several factors. Management practices do play a large role in piglet success. Influences during gestation such as increased intrauterine crowding, decreased placental efficiency and exceeding the capacity of the sow have been shown to negatively affect piglet growth. All of these factors can lead to a larger in-litter variation of piglets born. Bauer et al. (1998) showed that as the number of piglets born per litter increased the mean weight of each piglet per litter decreased and the weight of the lightest piglet per litter decreased. Perry and Rowell (1969) found that as the number of pig fetuses per horn increases,

so does the percentage of dead fetuses, particularly when there are greater than 6 fetuses per horn. These measurements were taken from dams at 31 to 113 days of gestation (Perry and Rowell, 1969).

Similarly, Pere and Etienne (2000) reported as litter size increased, uterine blood flow per fetus decreased. This implies reduced vigor at birth. Weight variation within litters can result in lost profits for the producer as there is increased labor and feed demands to ensure piglets arrive at market weight as a group and there are often delays in finishing times. For this thesis the hypothesis is that in order to reduce littermate variation of birth weight, increased uterine blood flow may be necessary. In the following literature review we will briefly discuss how the uterine environment, including blood flow, conceptus location, placental function and ovulation rate; along with maternal environment, nutrition and exercise can effect offspring development and meat quality in swine.

Uterine Blood Flow

In order for the maternal body to support pregnancy it needs to undergo numerous physiological changes including increased blood volume, cardiac output, stroke volume, and heart rate (Stocke and Metcalfe, 1994). In the human, maternal plasma volume begins to increase in the first trimester, with an exponential increase during the second trimester, followed by a smaller increase during the third trimester (Stocke and Metcalfe, 1994). Following the increase in plasma volume, red blood cell volume increases during the second trimester followed by the greatest increase in red blood cell volume until birth (Stock and Metcalfe, 1994). The increase in red blood cells is reflective of the increased need for oxygen delivery to the uterus, where during the latter half of pregnancy the gravid uterus consumes 2.5-fold more oxygen compared to skeletal muscle, myocardium, and kidneys (Thornberg et al., 2006). This increase in

blood volume is essential in order to support the development of the uteroplacental vascular bed while still maintaining standard blood flow to other organs in the body (Rosenfeld, 1984). In the pig, plasma volume and total blood volume decrease during the first seven weeks of gestation and, beginning at approximately d 50 after mating, increase until parturition (Anderson et al., 1970; Jezkova et al., 1977). The increase in total blood volume from mating to d 110 of pregnancy is approximately 30% (Anderson et al., 1970). The greatest increase in plasma volume was during the period in which the fetuses were growing most rapidly (Pomeroy, 1960; Elsley et al., 1968).

In the pig, uterine blood flow increases from d 19 of gestation until stabilizing at d 50 (Ford and Stice, 1985). Between d 50 and 90 of gestation, uterine blood flow remains constant at 1.34 liters/min per horn (Hard and Anderson, 1982a). Ford et al. (1984) reported that uterine blood flow was constant from d 92 of gestation until parturition (1.57 liters/min). Others report that between d 44 and 111 of gestation, total blood flow to the porcine uterus does not increase beyond normal parameters with an increased number of fetuses. It is reported that uterine blood flow per fetus decreases with increasing litter size (Pere and Etienne, 2000). Reynolds et al. (1985) characterized uterine blood flow in the sow from d 70 to 110 of gestation. During this period they observed uterine blood flow to remain constant across day of gestation with uterine blood flow being 1.58 liters/min on d 70 of gestation; 1.46 liters/min on d 90 of gestation and 1.48 liters/min on d 110. Expressed per unit of fetal weight, Hard and Anderson (1982a) found from d 92 of gestation until term, uterine blood flow per kg of fetal weight decreased quadratically, concluding that this decline was driven by the rapid increase in fetal weight during this time while uterine blood flow remained steady.

Researchers have used various methods to try and influence uterine blood flow in the pig including feed withdrawal (inanition) and litter size manipulations. Many of these studies have indicated that the maternal system will go to great lengths to sacrafice itself in terms of maternal body weight in order to maintain fetal development. Hard and Anderson (1982a) described uterine blood flow as unchanged for the duration of a 40 day inanition and highly correlated to litter size and fetal weight. Similarly, Reynolds et al. (1985) demonstrated that uterine blood flow was highly correlated with number of fetuses per horn but when expressed per fetus, uterine and umbilical blood flows were negatively correlated with the number of fetuses per horn. Pere and Etienne (2000) supported this by demonstrating that by creating a larger uterine environment through the use of oviduct ligation (LIG) and hysteroovariectomy (HHO). Blood flow measurements were taken from d 44 to 111 of pregnancy and steadily increased in all three groups during gestation measuring at 2.1, 2.3 and 2.4-fold increase at d 111 compared to d 44 in LIG, CTR (control), and HHO groups respectively. Although the rate of blood flow per fetus (mL per min per fetus) did not differ between groups, amount of blood flow per fetus (uterine blood flow per kg fetus) was affected by litter size. Blood flow was greater in uterine horns with more fetuses (4-5 fetuses per horn and 6-8 fetuses per horn vs. 2-3 fetuses per horn; 4-5 and 6-8 fetuses per horn did not differ) however blood flow per fetus was greater in uterine horns with fewer pigs, 2-3 fetuses per horn was greater than 6-8 fetuses per horn, with 4-5 fetuses per horn being intermediate (Pere and Etienne, 2000).

Uterine blood flow is not the only factor guiding fetal growth and development. Fetal growth has been shown to be influenced by many factors including genetic, epigenetic, maternal maturity, maternal nutrition, and environmental cues (Wu et al., 2006) with uterine environment known to affect fetal size (Wilson et al., 1998). However fetal losses can occur at any time point

of gestation. Foxcroft et al. (2009) provided an accurate depiction of the distribution of fetal losses during pregnancy, with a total embryonic loss of 40-60% and this will be discussed more below.

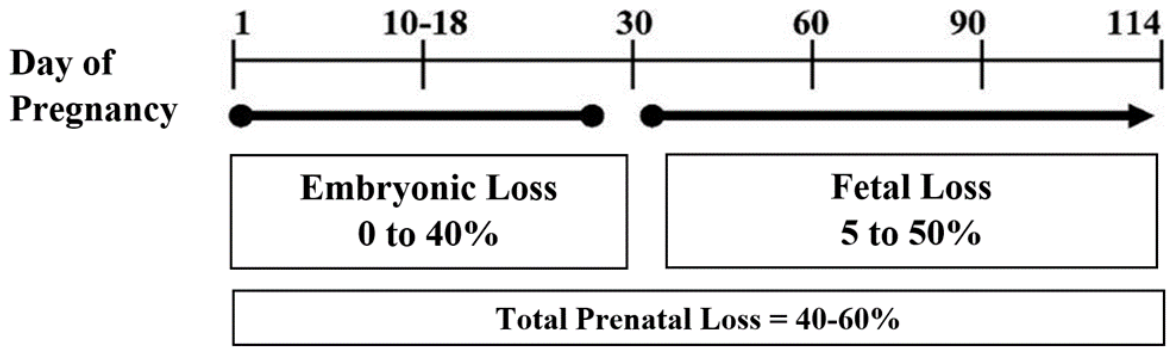

Figure 1.2. Schematic of prenatal losses during swine gestation. (Modified from Foxcroft et al., 2009).

Uterine Capacity

The concept of uterine capacity was established from different experimental approaches used to study uterine crowding in the pig, including uterine ligation, oviduct resection, unilateral hysterectomy and ovariectomy (UHO), and superovulation and embryo transfer. It was concluded that when the number of embryos exceeded 14, intrauterine crowding was a limiting factor for litter size born (Dziuk, 1968; Foxcroft et al., 2009).

One particular model that was used for several generations, was the unilateral hysterectomy ovariectomy (UHO) model where UHO is the surgical removal of one uterine horn and one ovary to reduce the uterine space available without changing the number of potential embryos. Knight et al. (1977) found through the use of UHO that even though the number of corpora lutea remain the same compared to intact control sows (indicating equal ovulations), there is a significant decrease in fetal growth after d 40 of gestation and fetal mortality increases

due to the limited uterine capacity. With similar ovulation rates coming from the remaining ovary, and half the uterine space, the potential for increased embryos was present resulting in severe uterine crowding, and therefore more intrauterine growth restriction (IUGR). Pigs exhibit the most severe, naturally occurring, IUGR. Intrauterine growth restriction can be defined as impaired growth and development of the mammalian embryo/fetus or its organs during pregnancy (Wu et al., 2006). Two of the major contributors that influence IUGR and impair fetal growth are insufficient uterine capacity resulting in reduced placental size and inadequate maternal nutrition. Uterine capacity is a complex trait composed of uterine, placental, and fetal factors that influence the survival of fetuses in a crowded uterine environment (Vallet and Freking, 2006). Before d 35 of gestation, pig embryos are uniformly distributed within the uterine horn (Anderson and Parker, 1976). It is after d 35 that uterine capacity becomes a limiting factor for fetal growth (Wu et al., 2006). This decrease in fetal size is due to the decrease in placental weight, length, and surface area. Traditionally fetal weight is correlated with placental weight (Knight et al., 1977). Recent studies however, have demonstrated that functionality and vascularity are more closely correlated to rate of fetal growth rather than placental weight (Reynolds et al., 2005).

Ovulation Rate

In recent years, many producers made it a priority to select their replacement gilts based on ovulation rates. To demonstrate selection for ovulation rates, Johnson et al. (1999) conducted a study that included 11 generations of selection for increased ovulation rate, followed by 3 generations of selection for litter size in the pig. Johnson et al. (1999) showed increased ovulation rate from 14 to 20.5 ova, and numbers of live pigs born (+1.4). However, they also experienced increased number of stillborns, decreased piglet birth weights, and decreased

postpartum viability in terms of fewer piglets weaned compared to the unselected control line. This drive to continually increase the number of pigs per sow per year may be causing producers to be sacrificing prenatal development, fetal weight, and influencing postnatal growth. Variations in within-litter birth weights are established by d 35 of gestation (Foxcroft et al., 2009). This within-litter coefficient of variance of weight averages 10-11% on d 27 or gestation but then doubles during fetal growth and maturation to reach 20-22% variation at birth (Quesnel et al., 2010). Producers should be looking more into uterine capacity when selecting sows versus ovulation rates.

Uterine Location

Position of the fetus in the horn of the uterus also has a role in determining fetal growth and weight. This has been demonstrated in rabbits (Rosahn and Greene, 1936), mice (McLaren, 1965), guinea-pigs (Ibsen, 1928) and pigs (Waldorf et al., 1957). Porcine fetuses near both ends of the uterus (i.e. the uterotubal junction and the cervix) are generally larger than those this the middle of the horn with the difference in growth particularly evident in late gestation in pregnancies where the number of fetuses exceeds 5 per horn (Perry and Rowell, 1969). Perry and Rowell (1969) observed that fetuses located second from the oviductal end of the uterus were heavier throughout gestation. However, the weight of the fetuses at d 30 of gestation did not differ between locations in the horn. It is also worth noting that on d 30, placental weights were heaviest at the oviductal end of the uterus but declined becoming lowest at the cervical end of the uterus. Wise et al. (1992) observed at d 70 and 104 of gestation, fetal weights began to differentiate with fetal and placental weights being heavier at the cervical and uterotubal ends of the horn. However, runts can be present at any position in the uterus (Perry and Rowell, 1969), with their size being more related to the size of the placenta (Wu et al., 2006). The post-natal

consequences of IUGR are varying and often still detectable at harvest of the animal or breeding (see **Table 1.1.**).

Table 1.1. Consequences of intrauterine growth restriction (modified from Wu et al., 2006).

Item	Species
Body Composition and meat quality	Pig and Sheep
Decreased skeletal muslce fiber number, increased whole-body and intramuscular fat mass, increased connective tissue content, and reduced meat quality	
Growth Performance	Pig, Sheep and Horse
Reduced whole-body and skeletal muscle growth rates, and reduced efficiency of feed/forage utilization	
Neonatal Health and adjustment	Pig, Sheep and Horse
Increased morbitiy and mortality, reduced survival, maladjustment to the extrauterine life, and increased stillbirths	
Organ Dysfunction and abnormal development	Pig and Sheep
Testes, ovaries, brain, heart, skeletal muscle, live, thymus, small intestine, and mammary glands	

Oftentimes (~35%), if a piglet is less than 0.8 kg at birth, it will be born dead (Quiniou et al., 2002). Preweaning survival rates decrease progressively from 95 to 15% as piglet birth weights decrease from 1.80 to 0.61 kg. Taking into account, 15 to 20% of live born piglets are born weighing less than 1.1 kg, resulting in their chances of survival to weaning and postnatal growth rates being severely reduced (Quiniou et al., 2002; Wu et al., 2006). These newborn piglets with IUGR often suffer from necrotizining enterocolitis which is a serious disorder of the small intestine that impairs intestinal function, most notably the synthesis of arginine, an essential amino acids for piglets but one that is deficient in the sow's milk (Wu et al., 2006). This inability to properly absorb nutrients is a major cause of piglet mortality.

Along with location in the horn, fetal sex may play a role in piglet birth weight. Wise et al. (1992) stated that males fetuses are heavier at d 70 and 104 of gestation compared to females and that sex of the neighboring pigs will influence birth weight of resident pigs. At d 104 of gestation, pigs with both neighboring fetuses of the opposite sex had a lower fetal weight compared to pigs with neighboring same sex siblings for both males and females (Wise et al., 1992).

Perhaps one of the most important factors to consider when discussing fetal growth is the function of the placenta itself. The placenta is the organ that transports nutrients, respiratory gases and wastes between the maternal and fetal circulatory systems. The growth of the placenta is crucial for the growth of the fetus and in a normal pregnancy the uterine and placental blood flows increase throughout gestation to meet the metabolic needs of the growing fetus (Reynolds et al., 2005). Pigs have a diffuse placenta which is the least invasive of all placental types and relies heavily on surface area for nutrient exchange from the maternal to fetal sides. A rapid increase in placental size occurs between d 20 and 30 in the pig. This rapid growth then reaches a plateau around d 70 before increasing again after d 100 of gestation (Pomeroy, 1960; Knight et al., 1977). Uteroplacental blood flow is a major factor that influences the availablity of nutrients for fetal growth and development. The rates of uteroplacental blood flows depend largly on placental vascular growth,which results in angiogenesis and placental vascularization (Vonnahme and Ford, 2004).

While ovulation rate is similar between U.S. and Chinese pig breeds, Chinese Meishan pigs produce three to five more pigs per litter than U.S. breeds (Wilson et al., 1999). Meishan sows are known for their increased placental efficiency, which is fetal weight divided by placental weight, compared to Yorkshires. Vonnahme et al. (2002) reported Meishan placentas

and fetuses were markedly smaller and lighter than the Yorkshire conceptuses on d 111 of pregnancy however there was no difference in the number of fetuses or percentage of viable conceptuses. In a study by Wilson et al. (1999), boars and gilts were selected based on either higher (A group) or lower (B group) than average placental efficiency. When boars and gilts selected by placental efficiency reached sexual maturity and were bred, A group females farrowed more live pigs per litter than B group females (12.5 ± 0.7 vs 9.6 ± 0.5). Although the piglets from A group sows were approximately 20% lighter on average than B group piglets (1.2 ± 0.1 vs 1.5 ± 0.1 kg) the placentas of A group were approximately 40% lighter (250 ± 10 vs 347 ± 15 g) resulting in a marked increase in placental efficiency (Wilson et al., 1999). Placental efficiency however is not just reflected by placental weight or size but also depends on factors such as placental microvascular density, interdigitation of the placenta with the maternal endometrium and placental blood flow (Wu et al., 2006). To evaluate the nutrient uptake by the uterus or the fetus, researchers use the basis of the Fick principle: Uptake = blood flow x (A-V), where (A-V) represents the difference of a substance in arteriovenous concentration across the uterus or the fetus (Bell and Ehrhardt, 2002). In sows, at d 77 to 110 of gestation there are significant correlations between placental weight and placental blood flow, between placental weight and fetal weight, and between placental blood flow and fetal weight (Wootton et al., 1977). Runt piglets are associated with a small placenta and low rate of placental blood flow. In addition to lowered blood flow, runt piglets also experience reduced placental transport of leucine at d 45, 60, and 100 of gestation (Finch et al., 2004).

Maternal Nutrition

With the development of more prolific sows and progeny with increased genetic potential for prolificacy, sows have increased nutrient requirements during gestation (Ball and Moehn,

2013). Maternal nutrition can be manipulated to impact fetal development and growth at various stages of pregnancy and including offspring muscle growth. Essential amino acids play a crucial role in the development and growth of the placenta and the fetuses (Bell and Ehrhrdt, 2002). An amino acid often researched is arginine. Arginine is involved in numerous roles in animal metabolism and is a common substrate for nitric oxide (NO) and polyamine synthesis (Wu et al., 2006). Nitric oxide is a major endothelium-derived vasorelaxing factor and has an important role in regulating placental-fetal blood flows which in turn can be translated into increased transfer of nutrients and oxygen from the mother (Wu et al., 2006). In a study conducted by Garbossa et al. (2015), pregnant sows were fed ractopamine and arginine supplements from d 25 to 53 of gestation to evaluate effects on fetal muscle development and performance and carcass characteristics of progeny. Sows were divided into 4 dietary treatments; 1) control diet, 2) control diet + supplementation of 1.0% of L-Arg, 3) control diet + 20 mg/kg of ractopamine HCl or 4) control diet + supplementation of 1.0% L-Arg + 20 mg/kg ractopamine HCl. The number of piglets born (total and alive) and the percentage of mummified piglets was not significantly different between treatments. However, the number of stillborn piglets was greater for all treatments compared to control. While litter weight was not significantly different, individual birth weights of piglets fed ractopamine were 11% greater than those not fed ractopamine (Garbossa et al., 2015). It is also worth note that the weight distribution at birth was improved by ractopamine and ractopamine+Arg diets compared to control group with a greater percentage of piglets having birth weights greater than 1.6 kg. Similarly, Quesnel et al. (2014) showed that supplementing sow diets with L-Arg during the last third of pregnancy did not influence mean piglet birth weight, but it did reduce within-litter variation of birth weight with a decrease in variation of 4.3% of total born and 4.8% of born alive piglets in the L-Arg supplemented group

versus the control group who received no supplementation. It is thought that L-Arg when fed in the diet, can promote both placental efficiency and fetal growth. Maternal underfeeding of energy and protein impairs embryonic/fetal growth in pigs (Wu et al., 2006). Ashworth (1991) demonstrated that reducing intake of complete rations by 50% for 2 estrous cycles before mating decreased fetal weight at d 30 of pregnancy in gilts. A similar study conducted by Vinsky et al. (2006) showed that restricting feed in primiparous sows by 50% during lactation before mating reduced the weight of both male and female fetuses as well as the survival of female embryos at d 30 of gestation. Birth weights as well as brain and liver weights were reduced in the progeny of gilts fed a protein-deficient diet throughout gestation (Pond et al., 1969, Atinmo et al., 1974, Wu et al., 2006). Contrary to undernutrition of mothers, maternal overnutrition can pose just as harsh of an impact on fetal growth and development. Maternal overnutrition, (high energy, high protein, or both) during the premating period or early pregnancy often results in increased porcine embryo and fetal mortality (Ashworth, 1991). Similar to underfeeding, overfeeding once pregnancy has been established retards fetal growth in pigs (Cole, 1990) and adolescent sheep (Wallace et al., 2004). Nissen et al. (2004) found that overfeeding both energy and protein between d 25 and 50 of gestation had no beneficial effect on muscle fiber number or area in the offsping but instead reduced skeletal muscle weight of newborn piglets due to smaller fiber size. However Dwyer et al. (1994) demonstrated that progeny of sows supplemented with doubled feed intake during d 25 to 50, immediately before fiber hyperplasia; d 50 to 80, during fiber hyperplasia; or d 25 to d 80, covering hyperplasia; all had significantly greater mean secondary:primary fiber number ratio. Similar to the benefits seen by Dwyer et al. (1994), Liu et al. (2016) reported an improved fetal digestive traits after mothers were supplemented a high energy diet (HED) throughout gestation. They reported increased body weights in fetuses, birth,

and weaning of piglets from HED versus control (+20%, +19% and +25% respectively). Additionally the offspring from HED sows had improved small intestine measurements and increased digestive enzyme activity. One enzymatic activity of particular mention is increased activity of lactase in the jejunum (+68% compared to CON; Liu et al. 2016). This enzyme is particularly critical after birth for the piglet to be successful at nursing and converting nutrients to provide energy.

Maternal Exercise

There are several physiological changes that occur during pregnancy, such as increased uterine blood flow and oxygen consumption, that also occur during exercise. Both exercise and pregnancy have been extensively studied individually, however there is very limited data on the interconnection of one to the other. McKirnan (1986) measured blood flow, using the microsphere technique, to various organs in trained and untrained non-pregnant pigs at rest, during “moderate” exercise and during “maximal” exercise on a treadmill. Blood flow to the brain was greater in untrained pigs compared to trained pigs at rest and during moderate and maximal exercise. The heart was the only other organ in untrained pigs to show an increase in blood flow compared to trained pigs but only during moderate exercise. At moderate exercise, blood flow to the biceps femoris, intestine, liver and kidney did not differ between trained and untrained pigs. During maximal exercise, blood flows to the biceps femoris muscle and intestine were greater in trained than untrained pigs, but no difference was seen for the heart, liver, and kidneys (McKirnan, 1986). These measurements were taken in non-pregnant growing Yucatan and Hampshire pigs. Specifically, for this discussion, there is limited data involving pregnant sows and exercise and the postnatal impact on progeny. Hale et al. (1981) used trained exercised and non-exercised pregnant pigs in an experiment to measure the effect of exercise on farrowing

and weaning performance in swine. No significant effects were observed between exercised or non-exercised animals on birth weight or weaning weights. In sheep, research has shown that cardiac output of ewes exercised during the last 40 days of pregnancy increased as a result of an increase in heart rate alone as there was no change in stroke volume (Orr et al., 1972). Studies conducted by Curet et al. (1976) supported Orr et al. (1972) demonstrated that vessel resistance must decrease in order for changes in heart rate and cardiac output to be experienced with no change to blood pressure being reported. In ewes following exercise, uterine blood flow measurements did not change from levels recorded prior to exercise (683 ± 142 ml/min vs. 801 ± 74 ml/min, respectively; Curet et al., 1976). Although the levels of blood flow remained unchanged following exercise, the distribution of blood, measured by microspheres, was increased toward the cotyledons and decreased from the myometrium and endometrium. In contrast, Lotgering et al. (1983) saw a decrease in uterine blood flow during prolonged exercise in the ewes evaluated at d 117 to 138 of gestation, with the decrease in blood flow becoming greater with more intense exercise and longer duration. This decrease was sustained throughout exercise, regardless of exercise intensity. The study was outlined as 10 min at 70% oxygen consumption, 10 min at 100% maximum oxygen consumption, and 40 min at 70% maximum oxygen consumption. Maximal oxygen consumption was classified as open-mouthed panting with protruding tongue in combination with a staggering gait (Lotgering et al., 1983). It is important to note that Lotgering et al. (1983) measured uterine blood flow during exercise while Orr et al. (1972) and Curet et al. (1976) measured uterine blood flow just following exercise. This is important because Lotgering et al. (1983) did illustrate that the decrease in uterine blood flow they saw, rose to pre-exercise levels shortly after the completion of exercise. A complete comparison of these studies however is difficult due to differences in procedures relative to the

time of gestation, intensity, duration of exercise and duration of acclimation periods. Harris et al. (2013) in a study to evaluate the effects of maternal exercise on fetal growth, umbilical blood flow and birth weights in swine found that gilts allowed to exercise had greater umbilical blood flow compared to control. Although indices of vascular resistance were not affected by maternal treatment, exercised gilts achieved peak pulsatility index earlier than control, indicating that the ability for vasodilation occurred earlier in pregnancy when dams were allowed to exercise.

Evaluating oxygen consumption is also important for evaluating the impact of exercise on developing fetuses. Maternal oxygen consumption has been shown to increase from control values during short duration exercise (10 min) in both 70 and 100% maximum oxygen consumption. Uterine blood flow is inversely related to intensity and duration of exercise as uterine blood flow is inversely related to heart rate and heart rate is positively related to oxygen consumption (Lotgering et al., 1983, Chandler et al., 1985). Chandler et al. (1985) found a 20% increase in maternal oxygen concentration but no change in oxygen uptake by the uterus, umbilical cord or uteroplacenta during exercise. Exercise could affect litter size and when exercise is implemented during gestation occurs plays a role in litter size (Garris et al., 1985).

Although exercise alone is known to be healthy for the adult system, the impacts of exercise on the fetus is not fully understood. Fetal stress results in the release of catecholamines and changes in heart rate, blood pressure, blood flow distribution, and hematocrit levels in the mother (Lotgering et al., 1983). Through his work with the ewe, Lotgering et al. (1983) described that fetal glucose levels remain unchanged during exercise even though ewe glucose levels increase when exercised for 40 min at 70% maximum oxygen consumption. Fetal lactate levels increased when ewes were exercised for 40 min at 70% maximum oxygen consumption and were unchanged when ewes were exercised for 10 min at 70% and 100% maximum oxygen

consumption (Lotgering et al., 1983). Chandler et al. (1985) observed a 45% increase in fetal arterial concentration of lactate in fed, exercised ewes. However maternal lactate increased 210%. Uterine and uteroplacental uptake of lactate increased dramatically and umbilical net uptake decreased (Chandler et al., 1985). Chandler et al. (1985) attributed this to an increase in umbilical arterial lactate concentration as umbilical venous levels remained unchanged resulting in a net decrease in umbilical net uptake of lactate. This increase appears to be related to the duration of exercise. This is noteworthy as lactate levels at birth can be used as a predictor of fetal viability in pigs (Herpin et al., 1996). Piglets with higher lactate at birth have lower viability as pigs that did not survive to 10 days of age had higher blood lactate levels at birth compared to piglets surviving to d 10 of age.

The impact of maternal exercise on progeny performance later in life is not heavily researched. Harris et al. (2013) results showed that exercised gilts had less fully formed fetuses born and a tendency for number of piglets born alive to be lower than control animals (11.0 ± 0.8 vs 14.0; 9.5 ± 1.2 vs 14.0). Growth throughout lactation and weaning weights were not affected by treatment.

Maternal Environment

Throughout all stages of gestation, fetuses respond to both internal and external environmental stimuli through development and growth (Wu et al., 2006). While genetics can be viewed as setting up the foundation upon which external environmental influences build, there are several environmental factors that can impose changes to regulatory aspects of fetal growth (Rehfeldt et al., 2010). Nutrient partitioning (Redmer et al., 2004), reproductive limitations of uterine capacity (Wu et al., 2006) and the surrounding external maternal environment (Lay et al., 2008) influence the physiology of the fetus. These influences on prenatal physiology of the fetus

can have consequences in postnatal life. Intrauterine growth restriction, for example can influence body composition, meat quality, growth performance, neonatal health and adjustment, organ dysfunction, and abnormal development as outlined by a review by Wu et al. (2006).

Implications of Birth Weight

Weight at birth can potentially be a predictor for postnatal performance from the farrowing house to the finishing barn. Piglets with lighter birth weights continue to have lighter body weights throughout all stages of production (Powell and Aberle, 1980; Quiniou et al., 2002; Schinckel et al., 2007). Alongside the differences in body weights that have been observed, birth weights may affect growth, backfat and longissimus muscle area as well as muscle fiber number. Low birth weight piglets fail to increase their muscle fiber number or muscle growth during the postnatal period even when fed adequately (Hegarty and Allen, 1978). These runt piglets often exhibit lower growth rates of skeletal muscle and whole-body growth between birth and slaughter and utilize feeds less efficiently when compared against high birth weight littermates (Hegarty and Allen, 1978). Along with piglets being smaller overall, their survival rates can also be reduced as mentioned above. Fix et al. (2010) reported that only 18% of light weight pigs (≤ 1 kg) born alive survived to finisher placement compared to 66% of pigs > 1 kg. In this same study the authors demonstrated that as birth weight decreased, the likelihood of pigs being full value at harvest decreased ($P < 0.01$). Several studies have compared birth weights and subsequent performance of offspring. Birth weights were classed bottom 25%, middle 50% or top 25% birth weight. Pigs born in the bottom 25% weight group had a reduced average daily gain (Berard et al., 2008; Rehfeldt et al., 2008) feed efficiency (Gondret et al., 2006), increased feed intake (Berard et al., 2008), and increased days to slaughter (Gondret et al., 2006; Berard et al., 2008). These same pigs also had decreased hot carcass weight (Nissen et al., 2004; Rehfeldt et al.,

2008), longissimus (Gondret et al., 2006), semimembranosus (Gondret et al., 2006; Rehfeldt and Kuhn, 2006), semitendinosus (Nissen et al., 2004), increased percentage perirenal fat (Rehfeldt et al., 2008), percentage intramuscular fat (Rehfeldt et al., 2008), and backfat (Gondret et al., 2006) at slaughter. Conversely, Dwyer et al. (1993) upon comparing piglet birth weights found average daily gain correlated with birth weight only from birth to d 70. Muscle fiber number had no correlation with ADG from birth until d 70, inversely correlated to birth weight, but ADG became positively correlated with increased muscle fiber numbers after d 70. Gain to feed ratio was also positively correlated with muscle fiber number. Subsequent complications of slaughter management due to large within-batch variations of final weights then become a challenge (Boulot et al., 2008) especially in today's commercial systems where producers focus on an all-in all-out finishing system.

Muscle Development

The primary purpose for swine production is the production of meat products. The growth of muscle development begins prenatally and can be heavily influenced by the factors previously discussed. There are two developing types of muscle fibers in the fetal pig: primary fibers, which are formed by the rapid fusion of primary myoblasts between d 25 and 50 of gestation, and secondary fibers, these are formed on the surface of primary fibers between approximately d 50 to 90 of gestation (Foxcroft et al., 2009). During prenatal development these muscle fibers undergo contractile differentiation, resulting in the formation of slow-twitch, fast-twitch oxidative-glycolytic and fast-twitch glycolytic fibers (Wu et al., 2006). It is the secondary muscle fiber numbers however that are affected by the uterine environment with total number of fibers fixed at birth and is a major factor affecting the postnatal growth of the animal. Smaller piglets with a decreased number of primary fibers will have less opportunity for secondary

muscle fiber growth. Decreased fetal weight can stunt postnatal growth and alter body composition in terms of lean to fat ratio of the animal at the time of harvest. It has been suggested that this lowered potential is not only due to a lower birth weight but that IUGR may play a more complex role on developmental potential as well as maternal nutrition.

In a study conducted by Foxcroft et al. (2007) low birthweight littermates had reduced growth potential and poor carcass quality, linked to lower muscle fiber numbers at birth. In comparison with the average-sized littermates, intramuscular fat and connective tissue contents are greater in the small porcine fetus at d 86 of gestation and in postnatal pigs with prior experience of IUGR (Karunaratne et al., 2005). At similar adult weights, runt pigs had larger muscle fiber diameters, large quantities of intramuscular fat and lighter muscled carcasses (Hegarty and Allen, 1978; Powell and Aberle, 1980). This change in muscle composition can be translated to adverse effects on meat quality. Piglets that had experienced IUGR exhibited elevated levels of intramuscular lipids and low scores for meat tenderness (Gondret et al., 2005). Although overall performance of the progeny in the study by Garbossa et al. (2015) was not affected by treatment group, those animals who received either Arg, ractopamine or Arg+ractopamine had decreased number of semitendinousus muscle fibers (3.76, 4.58 and 4.70% respectively) compared to control and increased muscle fiber diameters (16.99, 16.34 and 17.36% respectively).

Developing muscle fibers can be highly sensitive to nutrient availability in utero as they are not tissues that are normally spared (i.e. brain and heart; Vallet and Freking, 2006). Maternal nutrition throughout gestation has an effect on piglet birth weight and secondary muscle fibers (Dwyer et al., 1994). Dwyer et al. (1994) demonstrated that increasing maternal nutrition (increased kg/d) from varying intervals between 25-80 days of gestation improved the fiber

number of pigs in the lower range of fiber number distribution, increasing the secondary to primary ratio of offspring.

Conclusion

In summary, there are many factors that can impact fetal growth and development including uterine capacity, uterine blood flow and placental function, maternal nutrition and environment. The impact of these factors during birth can have significant negative or positive effects on postnatal development. The interactions of these and other factors create a very complex system that needs further research to answer some key questions. Promoting an optimal intrauterine environment will not only ensure optimal fetal development but also enhance growth performance during postnatal life.

Statement of the Problem

As the swine industry continues to strive to increase its overall production, the need for further research to more efficiently reach production goals is essential. Problems facing swine producers range from housing systems to methods of euthanasia. With the past production practices of selecting for high ovulation rates the industry is reaching new heights in terms of litter size. However, these increased litter sizes bring about more challenges in terms of fetal development and piglet viability and postnatal growth. The industry has to not only look at the impacts of larger litter sizes in the farrowing house, but also in nursery and finishing sites. The potential impact of both litter size and maternal environment on muscle development can negatively impact both meat quality and the producer's bottom line.

The ways in which researchers can try to impact fetal growth can largely vary. For the purpose of this thesis we focused was to determine if uterine blood flow can be influenced, and if so, would an increase in uterine or umbilical blood be beneficial to carcass quality in the pig.

Our hypothesis is that increasing uterine blood flow during critical times of fetal development will increase piglet viability at birth and have lasting postnatal effects in terms of improved muscle development and meat quality.

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CHAPTER 2. EFFECTS OF VASOACTIVE COMPOUNDS ON UTERINE BLOOD FLOW IN GILTS

Abstract

In today's swine industry the low viability piglet is one of the greatest economic and social challenges on the farm. These piglets not only put additional stress on the farm workers but also are a loss of valuable economic return for the producer. One way to potentially improve piglet viability is through the use of vasodilating compounds to improve uterine blood flow in the pregnant sow. The objective of this project was to infuse five different drug compounds directly into the blood stream of cycling crossbred gilts (n=24) at varying doses to elicit a response of increased uterine blood flow. If there would be a promising compound, the compound would be introduced into pregnant swine. NDSU researchers were blind to compounds provided by Zoetis. Conclusions are based upon blood flow results and treatment dosage.

Introduction

A major obstacle within the swine industry is preweaning mortality of piglets, particularly from low viability piglets born. Losses include both economic and social aspects. From an economic standpoint, the greatest losses are due to sows lying on piglets not strong enough to escape from under the sow as she changes postural positions and the inability for piglets to "fight" for their spot on the sow in order to consume enough colostrum. The greatest prewean mortality of piglets is within the first 3 days of life (Ketchem and Rix, 2015) however, their viability early in life can significantly impact how they grow and perform in the nursery and finishing barns (Powell and Aberle, 1980; Quiniou et al., 2002; Schinckel et al., 2007). Also, there are severe social impacts from low viability piglets. For piglets that are low viability, the

current approved AVMA method for euthanasia is blunt force trauma to the head (AVMA, 2013). This image of euthanasia has major social and consumer implications influencing the public's perception of the swine industry. One way which we can improve viability and strength of the neonatal piglet is to enhance uteroplacental blood flow during pregnancy (Hard and Anderson, 1982a; Pěre and Etienne, 2000). In this preliminary study, we investigated five different drug compounds (provided by Zoetis) to determine if they could increase uterine blood flow in cycling, non-pregnant gilts. Our objective was to test if direct infusion of these compounds into the circulatory system would directly enhance uterine blood flow.

Materials and Methods

All procedures were approved by North Dakota State University (NDSU) Animal Care and Use Committee (#A15020). Twenty-four mature, cycling cross-bred gilts with an average weight of 167.8 kg were used for the determination of blood flow to the uterus with a Doppler Transonic flow probe. The gilts were individually housed at the NDSU Animal Nutrition and Physiology Center in Fargo, North Dakota. Estrous synchronization was achieved by using Matrix (Merck Animal Health, Altrenogest solution 0.22%), a progestin-containing feed additive. Gilts were hand-fed bread (mixed brands) with Matrix solution for 14 days to ensure ingestion. Gilts were then observed for signs of estrus 4 to 9 days after the completion of the Matrix regimen (per manufacturer's specifications). Gilts were scheduled for surgery 16 days after the last treatment of Matrix to ensure that all females were in the mid-luteal stage of their estrous cycle.

Surgeries began on January 7, 2015, with animals prepared for surgery by: 1) body weight recorded on Monday morning before surgery in order to ensure proper dosage of treatments; and 2) off feed for 24 hours and water 8 hours prior to surgery. Surgeries were

performed on Wednesdays, Thursdays and Fridays. Potential vasoactive compounds were provided by Zoetis and were blind to NDSU personnel. The order of drug assessment was determined by Zoetis. Vehicle controls (n = 4) were also conducted (one gilt for each vehicle). A total of 5 drugs being tested (n = 4 gilts per drug). All experiments were conducted on unconscious animals.

Gilts were placed in a sow crate in the surgical preparation area and sedated [cocktail of Telazol (Pfizer; 0.05 ml/kg) dissolved in xylazine (Rompun, Bayer; ~3 to 4 mg/kg) administered intramuscularly]. After gilts were initially sedated they were transported to the surgical suite and moved to a hydraulic table with her legs secured with rope and anesthetized with a mixture of oxygen and isoflurane (Abbott Lab) administered in a Drager closed-circuit system with soda lime for the removal of carbon dioxide. Atropine sulfate (MWI) was administered intramuscularly (0.05 mg/kg) to dry bronchial secretions prior to intubation. Fifteen minutes after atropine administration, intubation was attempted and successful in all animals. We utilized #10 trachea tubes (JorVet). Breaths per minute and body temperatures were recorded at intubation and monitored regularly: breaths per minute every 5-10 minutes and temperature every 15 minutes, throughout the length of the surgery.

Surgical sites were shaved and cleaned with warm water to remove larger debris followed by betadine surgical scrub, and sprayed with 70% ethanol after the final rinse. Following the preparation of the animal, catheters were put in place. Three catheters were utilized on each gilt using TYGON microbore tubing (Norton Performance Plastics). The catheters were pre-treated with TDMAC (tridodecylmethylammonium chloride, Polysciences Inc.) to prevent blood clotting. Two were placed into the cephalic veins, one for the administration of the drugs and continuous infusion of a sterile warmed lactated Ringers' solution (Hospira) and one for drawing

blood samples. Catheters were flushed with heparinized saline after compound infusion or blood collection. The third catheter was placed in the saphenous artery (~30.48 cm) for monitoring blood pressure with a Transbridge TBM4M pressure transducer (World Precision Instruments, Sarasota, FL), and pressures (measured in mmHg) were recorded using the WinDaq software program (DI-710 Series, Dataq Institute Inc., Akron, OH).

After catheters were placed, a midline incision (approximately 20-25 cm) was made posterior to the navel. All major blood vessels were either tied off with 0-braided silk ligature or cauterized using an electric cautery unit. The abdominal cavity was opened at the linea alba and through the mid-line abdominal incision the uterus and ovaries were exposed. At this time mid-luteal stage was confirmed in all but one animal, which was prepubertal and had no corpora lutea present (flow measurements were recorded and presented in the data below). The Transonic flow probe (4 mm) was placed around the main branch of randomly chosen uterine artery before the first branching and the empty space between the probe and the artery was filled in using Vaseline to ensure an accurate reading. The uterus was then returned to the body cavity and allowed to rest for ~45 minutes, and when stable uterine blood flow recordings were obtained (Transonic T206 small animal blood flow probe meter), compound infusions were initiated. Each dose was administered at 1 ml/min and flow and blood pressure were recorded electronically. Exactly 20 minutes after the end of the first infusion, blood samples were taken from the right cephalic vein, placed at 4°C, and serum separated and frozen to be sent back to Zoetis for analysis. For each dose, blood flow and blood pressures were collected for 45 minutes. This was repeated for each additional dose. At the completion of the experiment, the animal was euthanized with an overdose of sodium pentobarbital (Ethasol; Virbac AH, Inc.). The uterus on most gilts was removed and weighed. The animal and uterus were disposed of by incineration.

Calculations and Statistical Analysis

Treatment 51624 was excluded from the data analysis due to severe adverse reactions during drug administration.

In the calculations we included percent change within a dose (PWCI) and percent change overall (PCO) for blood flow and blood pressure. PWCI was found by Peak minus basal divided by basal. The peak was found by taking a section of data from the Windaq program after the administration of a dose that showed the peak level of blood flow. Basal was defined as the return to steady state 45 minutes after the administration of the dose. The equation used for PCWI was: [peak response (ml/min) – basal response (ml/min)] / basal response (ml/min). PCO was determined by taking the peak, found the same way as previously described, minus the control then divided by the control. Control was defined as the resting blood flow rate at the end of the equilibration period, prior to the administration of any drugs. The equation used for PCO was: [(peak response (ml/min) – control (ml/min) / control (ml/min)]. The generalized linear procedure of SAS was performed to determine the effect of treatment (48836, 51625, 83187, 08165), dose (1, 2, 3) and their interaction. Means were separated by least squared means procedure.

Results

Blood pressure (basal and peak within a dose) did not differ by treatment. Depending upon how blood flow was assessed, there were effects of treatment or dose (or both). Blood flow (basal; before next dose was administered) tended to be affected ($P = 0.12$) by treatment. LSMeans were separated by an unprotected F-test, treatment 08165 being greater than treatment 83187, with the others being intermediate. There was also an effect of dose on blood flow where blood flow decreased as increased concentrations of the treatment were administered. Moreover,

there was a tendency (P = 0.07) for peak blood flow to be greater in treatment 48836, compared to 83187 with the others being intermediate.

There were no differences (P > 0.19) in PCO of blood flow and blood pressure. However, when calculating percentage change from the baseline prior to dose administration, there was a treatment effect (P = 0.03). Treatment 48836 had a greater rise in blood flow compared to Treatments 83187 and 08165, with treatment 51625 being intermediate.

Table 2.1. Effects of drug treatments and dose on uterine blood flow of cycling gilts

	Treatment (Trt)					Dose				P-value	
Variable	48836	51625	83187	08165	SEM	1	2	3	SEM	Trt	Dose
BF[1] ml/min	84.45^{xy}	69.41^{xy}	59.00^{x}	113.83^{y}	16.58	117.38^{a}	66.84^{b}	60.81^{b}	14.36	0.12	0.02
PBF[2], ml/min	197.59^{x}	127.25^{xy}	85.17^{y}	144.18^{xy}	28.84	170.76	132.19	112.69	24.9	0.07	0.26
PCWI[3], %	242.03^{a}	103.56^{ab}	40.54^{b}	39.08^{b}	53.03	64.38	180.49	74.03	45.93	0.03	0.15
PCO[4], %	0.77	-0.14	0.75	4.73	1.69	0.62	1.79	2.18	1.47	0.19	0.74
BP[5]	89.75	96.41	80.67	86.92	4.78	88.75	88.06	88.50	4.14	0.15	0.99
PBP[6]	86.33	85.00	78.58	79.75	4.05	84.38	80.19	82.69	3.50	0.45	0.70

^{ab}LSMeans ± SEM within a row with different superscripts differ; $P < 0.05$

^{xy}LSMeans ± SEM within a row with different superscript differ with an unprotected F test; $P < 0.05$

[1]BF: Blood flow, ml/min (basal blood flow obtained just prior to the next infusion)

[2]PBF: Peak blood flow, ml/min (greatest value of blood flow after compound administration)

[3]PCW: Percentage change within a dose; [peak response (ml/min) – basal response (ml/min)] / basal response (ml/min)

[4]PCO: Percentage change overall; [(peak response (ml/min) – control (i.e. blood flow at the end of the equilibration period) / control]

[5]BP: Blood pressure, mmHg (obtained just prior to the next infusion)

[6]PBP: Peak blood pressure, mmHg (greatest value of blood pressure after compound administration)

Discussion

Based on the findings of this pilot study, the drug compound that had the greatest impact on uterine blood flow in cycling gilts was treatment 48836. While treatment 8165 also showed positive results, this may be due to greater initial values for blood flow when compared to other treatment groups. Treatment 48836 had the greatest percentage change within a dose, greatest percentage change overall and the highest peak blood flow of all the treatments performed.

Some possible considerations for future work in this area are as follows: 1) if a similar project is conducted, there should either be a greater range of doses administered, particularly lower concentrations. From our statistics, there was no effect of dose, or with increased dose blood flows decreased, so perhaps receptors were already saturated when initial doses were administered. A point of caution is that adding more doses to the current doses would greatly extend time of anesthesia. 2) Use of an *in vitro* system would be advantageous to investigate a wide range of doses. Uterine arteries could be taken from one animal and multiple compounds could be investigated on the same animal. This would be advantageous as well in order to eliminate animal to animal variation with pilot studies. 3) The overall objective is to investigate how maternal blood flow would be altered during pregnancy. Therefore, the responses that were obtained from this initial study may not be similar to what is occurring during different stages of pregnancy. Perhaps future studies could look at similar compounds, with added doses, in uterine and placental arteries in an *in vitro* system.

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CHAPTER 3. EFFECTS OF MATERNAL EXERCISE DURING GESTATION ON POSTNATAL GROWTH AND CARCASS CHARACTERISTICS IN SWINE

Abstract

Our laboratory has previously reported that pregnant swine allowed to exercise during mid to late gestation have increased umbilical blood flow to the piglets. Our objective was to determine how maternal exercise would impact postnatal growth and carcass parameters of their offspring at 6 mo of age. Yorkshire gilts were paired to either remain in their individual stall from d 40 to term (CON; n = 4), or exercise for 30 min 3 times per week from mid to late gestation (EX; n = 4). Within 12 h post partum, litter size was normalized within a pair of gilts. Pigs were weighed and backfat assessed. Pigs were harvested at 118 kg with organ masses recorded and carcass composition and meat quality determined. Data were analyzed with sow as the experimental unit. Maternal treatment did not impact offspring average daily gain. While there were limited organ and muscle mass differences due to maternal treatment, pigs from EX females had longissimus muscle with higher ($P \leq 0.05$) pH at 24 hr (5.36 vs 5.27 ± 0.03), decreased ($P < 0.05$) drip loss (6.31 vs 4.54 ± 0.48%), and increased ($P < 0.05$) L*(55.73 vs 52.40 ± 0.74) compared to CON. Maternal activity during gestation appears to have limited impacts on gross body measurements, but may be advantageous to carcass quality of their offspring. Future studies are needed to confirm that the increased meat quality relates to better pork for consumers.

Introduction

Maternal exercise during gestation has been studied in several species including the rat (Garris et al., 1985; Houghton et al., 2000), human (Jeffreys et al., 2006; De Oliveria Mello et al., 2012), sheep (Lotgering et al., 1983; Chandler et al., 1985) and pigs (Lay et al., 2008; Harris

et al., 2013). In rats, exercise during gestation decreased uterine blood flow but increased perfusion pressure and improved oxygen delivery (Lotgering et al., 1983; McMurray et al., 1993) and increased birth weight (Garris et al., 1985). Although the intensity and time point of gestation that exercise is implemented may have an influence on offspring, some studies have found no effect on birth weight from exercise (Hale et al., 1981), or decreased birth weight (Clapp III, 2003). The potential effects of maternal exercise on post-natal development of young is relatively unknown. However, it is known that offspring which experience reduced uterine or umbilical blood flows during gestation exhibit adverse phenotypes such as cardiac and metabolic diseases as well as obesity as adults (Louey et al., 2000; Lang et al., 2000; Baschat et al., 2000). In livestock, we know that carcass outcomes are also impacted by poor nutrition in utero (Funston et al., 2010; Wu et al., 2006).

In our laboratory, when female swine are allowed 90 minutes of activity per week during mid to late gestation, umbilical blood flow increases (Harris et al., 2013). While we reported little to no impacts on litter size, piglet birth or weaning weights, we hypothesized that the increased umbilical blood flow may alter postnatal growth and performance. The objective of this study was to investigate if maternal activity during gestation increased rates of growth and carcass measurements at slaughter in pigs.

Materials and Methods

Animal procedures

All procedures were approved by the NDSU Animal Care and Use Committee (#A0927). Gilts were subjected to exercise treatment as described in Harris et al. (2013). In brief, Yorkshire gilts (n = 8) were bred to a common boar (Hampshire x Duroc) and individually housed in farrowing stalls (57 cm x 176.5 cm) and assigned to treatment with a littermate pair. Within a

pair, one gilt was assigned to control (**CON**) which remained in the stall for the duration of gestation except for times when body weight was determined, while the other gilt (**EX**) was removed from her stall for exercise three times per week, for 30 min each time. The EX treatment was initiated on d 40, after the time when maximum uterine capacity occurs and the majority of embryonic and early fetal loss have passed (Webel and Dziuk, 1974; Foxcroft et al., 2006). On d 40 of gestation, duration of exercise was gradually increased with 10 min of exercise on d 40 and 41, 20 min of exercise on d 42 and 43, and 30 min of exercise on d 44 and every subsequent Monday, Wednesday, and Friday until d 104 of gestation.

Parturition occurred spontaneously and all gilts were observed. Farrowing characteristics have been previously published (Harris et al., 2013). Briefly, piglets were dried with a hand towel, and weighed prior to suckling. Within 12 hours of completion of farrowing, the lightest and heaviest male and female piglets were selected for necropsy to determine neonatal phenotypes (Harris, 2010). Thereafter, within an experimental pair, litter size was made equal. Weaning weights have been previously reported (Harris et al., 2013) and did not differ.

Growth, organ parameters, and carcass measurements

After weaning, piglets (n = 50) were divided into two groups of housing options. Twenty-three barrows were housed individually in order to collect feed intake and efficiency measurements. The remaining pigs (n = 27) were housed in group pens. All pigs were weighed every two weeks, beginning at 31.7 kg. Ultrasounds were conducted for 10^{th} rib backfat (BF) and longissimus muscle area (LMA) every four weeks beginning at 58.1 kg. Pigs were then harvested at 118 kg at the North Dakota State University Meat Science Laboratory. At slaughter, a modified necropsy was performed to obtain organ mass of heart, lungs, cardiac fat, spleen, liver, large intestine, small intestine, stomach, pancreas, omental-mesenteric fat, kidney, perirenal fat,

and lymph glands. Carcasses were fabricated 24 h after harvest and carcass composition and meat quality determined (NPPC, 2000).

Calculations and Statistical Analysis

All data were analyzed using PROC MIXED of SAS 9.2 (SAS Institute Inc., Cary, NC). Gilt was the experimental unit. Litter which the dam originated from (n = 4) was included in the random statement and treatment (CON or EX), sex, offspring pen type, and all interactions were included in the model. Repeated measurements were performed for ADG, weight, and carcass ultrasonography measurements. Average daily gain was calculated by taking weight measurements every two weeks, subtracting those weights from the previous measurements and dividing by the number of days between weight collections. Where random variables or interactions were $P \geq 0.20$, they were removed from the model. Absolute values of tissues and tissue as a proportion of BW (g/g) were evaluated. Data are presented as LSMeans ± SEM.

Results

Growth measurements

There was a sex by treatment interaction (P = 0.01) on body weight (**Figure 3.1.**). Barrows born to CON dams were heavier overall compared to all other groups. While there was no 3-way interaction of treatment by sex by week (P = 0.79), there was a week by sex interaction (P = 0.01) with males having a greater rate of gain between the 12 and 14 weeks and 22 and 24 weeks of age compared to females (**Figure 3.2A.**). There was a tendency for a week by treatment interaction (P = 0.09; **Figure 3.2B.**) where piglets from EX dams had decreased average daily gains at week 16, 18 and week 22 of age. There was a sex by treatment interaction (P= 0.01) on LMA (**Figure 3.3.**). Females from EX gilts had the smallest LMA compared to all other groups. There was no interaction of treatment by sex by week (P= 0.44), however there was a week by sex tendency (P= 0.09) with females tending to be have smaller LMA than males. There was a

week by sex interaction (P= 0.03) on backfat measurements (**Figure 3.4.**). While backfat increased in both sexes, it appears the rate of backfat deposition of the female was not as great as the male, although there were no statistical differences between sexes within a week upon means separation.

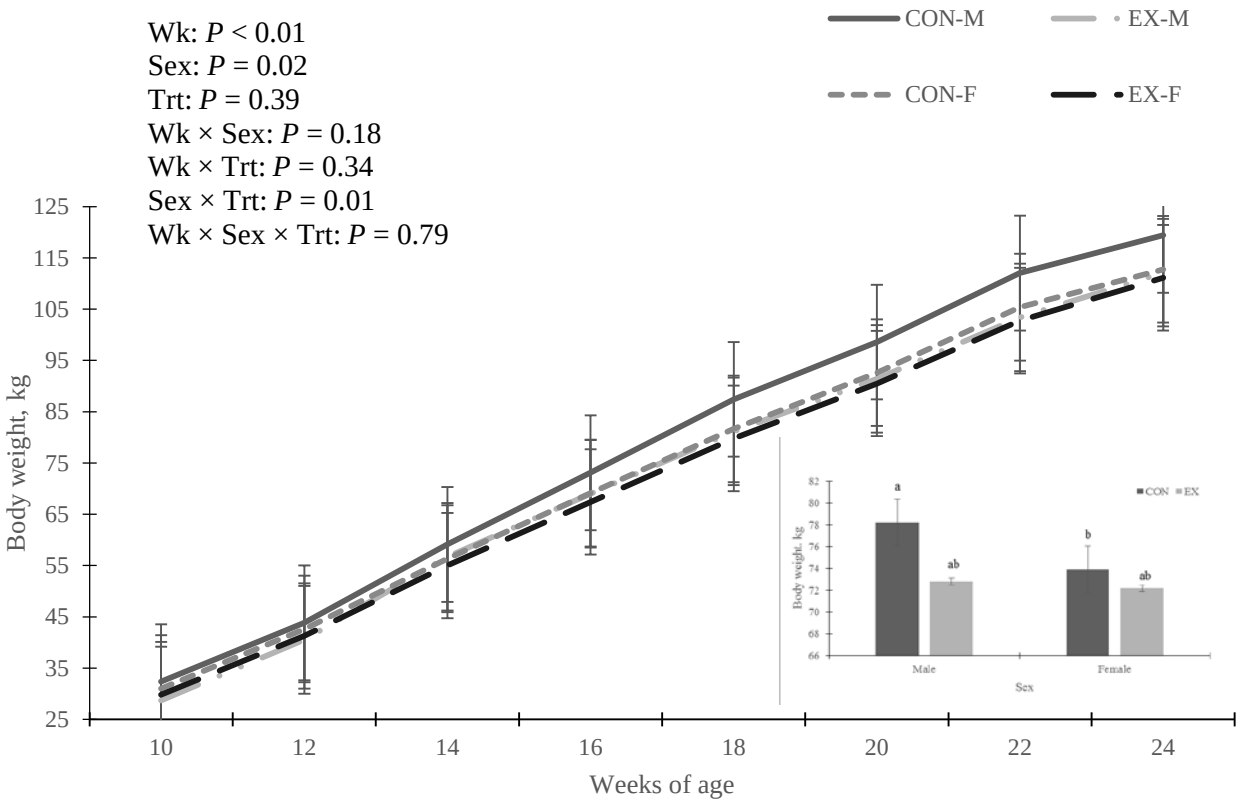
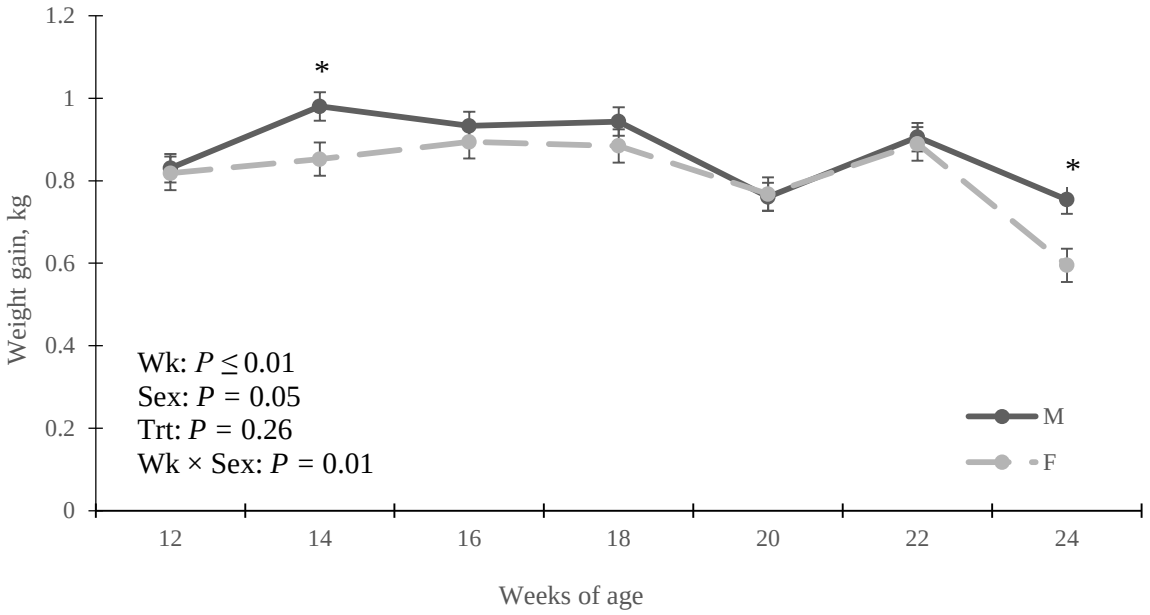


Figure 3.1. Body weight of offspring from gilts housed in stalls during gestation (CON) or exercised (EX) three times per week for 30 min from d 40 to 104 of gestation.

A.



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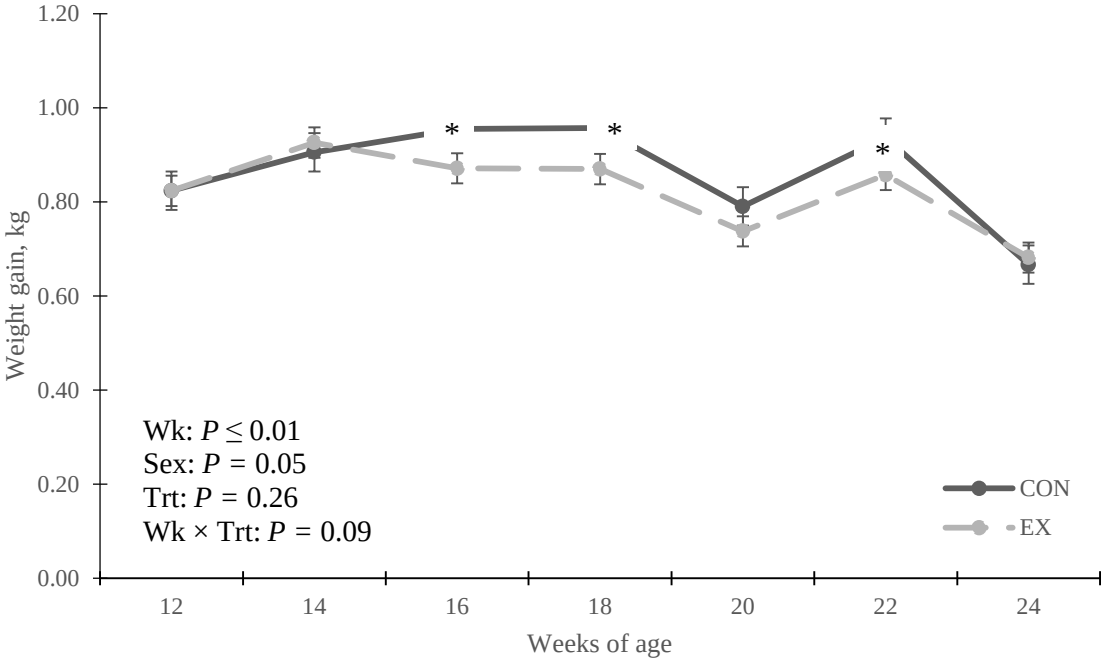


Figure 3.2. Average daily gain kg/day of all offspring from gilts housed in stalls during gestation (CON) or exercised (EX) three times per week for 30 min from d 40 to 104 of gestation. Week x sex effect (A). Week x treatment (B). * signifies $P \leq 0.10$.

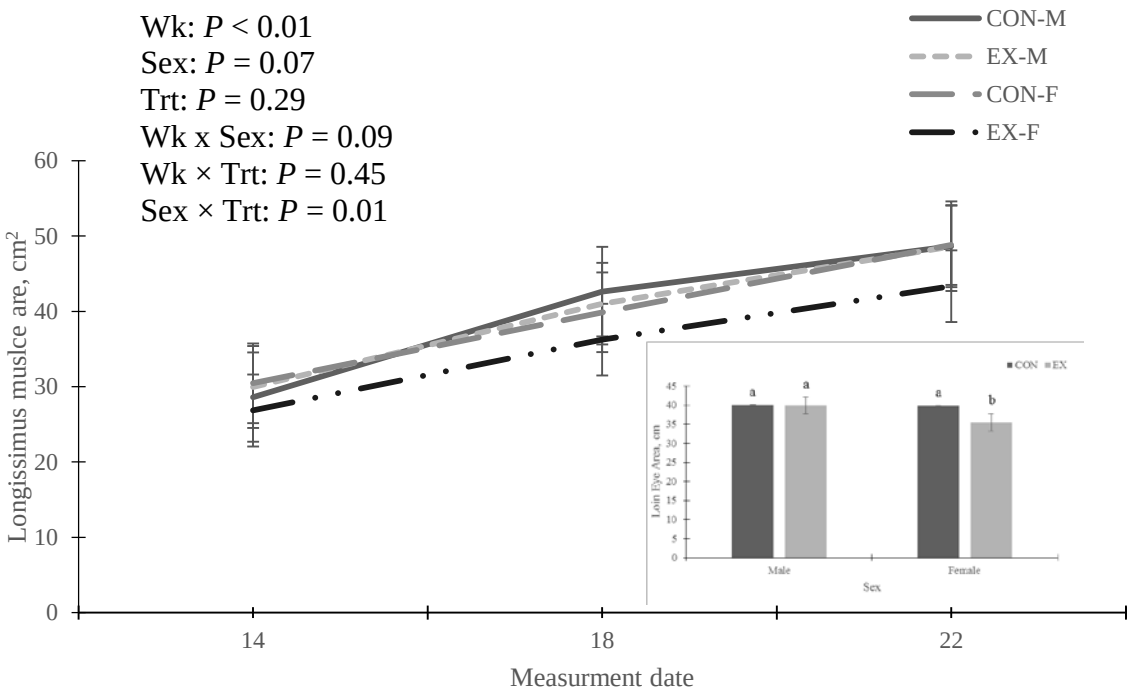


Figure 3.3. Longissimus muscle area of all offspring from gilts housed in stalls during gestation (CON) or exercised (EX) three times per week for 30 min from d 40 to 104 of gestation.

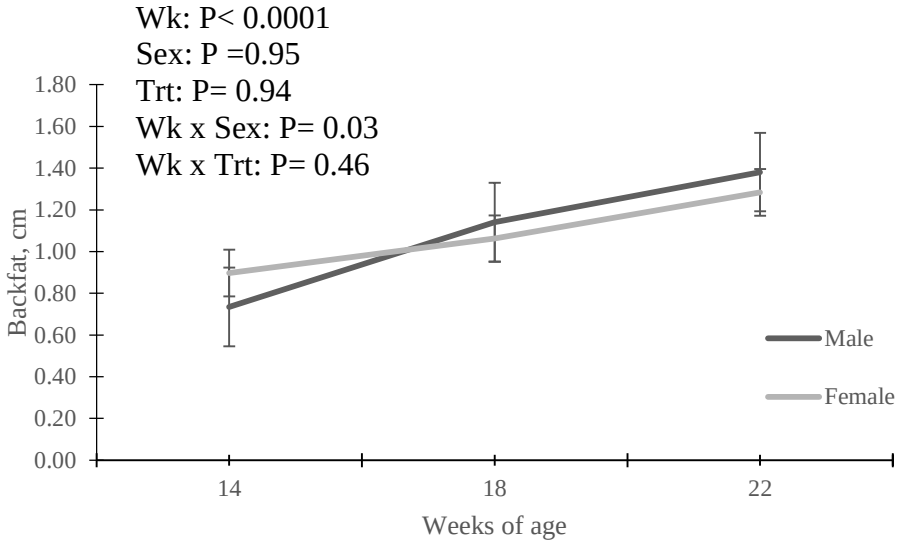


Figure 3.4. Backfat measurements collected via ultrasound of offspring from gilts housed in stalls during gestation (CON) or exercised (EX). Week x Sex effect.

Organ mass

There was no treatment by sex interaction ($P \geq 0.83$) for final body weight or EBW. While maternal treatment did not impact final body weight or EBW, there was a tendency ($P=0.08$) for EBW to be greater in male vs female offspring (**Table 3.1.**). There were a few organs where treatment by sex interactions were significant. While stomach weight (kg) was similar within a sex in CON, males had lighter stomachs compared to females from EX dams (**Figure 3.5A.**). When expressed relative to EBW, females from EX dams had the greatest relative stomach mass compared to all groups, whereas males from EX had the least (**Figure 3.5B.**). There was also a significant treatment by sex interaction for omental-mesenteric fat (kg and kg/kg EBW). While maternal treatment did not alter omental-mesenteric fat (kg and kg/kg EBW) in females, males from EX dams had less fat (kg and kg/kg EBW) compared to CON dams (**Figure 3.6A.**). Moreover, males had greater omental-mesenteric fat mass (kg and kg/kg EBW) compared to females from CON dams (**Figure 3.6B.**). There was a tendency ($P = 0.06$) for a treatment by sex interaction for cardiac fat mass with females having greater cardiac fat mass compared to males from EX dams, with both sexes from CON dams being intermediate (**Figure 3.7.**). There was only a main effect of sex when relative cardiac fat mass (g/ kg EBW) was calculated with males having greater ($P = 0.03$) cardiac fat mass compared to females (**Table 3.1.**). While there was no effect of offspring sex or maternal treatment, or their interaction on absolute spleen mass (**Table 3.1.**), there was an interaction ($P = 0.02$) for relative spleen mass (**Figure 3.8.**). Females from CON dams had the greatest relative spleen mass compared to all other groups. There was no effect of sex or maternal treatment for absolute pancreas weight ($P > 0.15$), however there was a tendency ($P = 0.09$) for an interaction in relative pancreas mass. While there was no effect of maternal treatment in female offspring,

males from CON had a greater relative pancreas weight compared to males from EX dams (**Figure 3.9.**). There was a tendency (P = 0.08) for females to have increased relative pancreas mass per EBW than males from EX dams (**Figure 3.9.**). Absolute small intestinal mass only tended to be affected by main effects of treatment (where offspring from CON were greater than EX dams) and sex (where males had greater small intestine weight compared to females; **Table 3.1.**), but there was a sex by maternal treatment interaction for relative small intestinal mass (**Figure 3.10.**). In male offspring, EX treatment resulted in piglets having reduced relative small intestinal mass compared to CON. Moreover, in offspring from EX dams, females had greater relative small intestinal mass compared to their male counterparts (**Figure 3.10.**). For all remaining organs (kg and kg/kg EBW), there were only main effects of treatment or sex of offspring. While absolute liver mass was not affected by treatment or sex (P > 0.15) there was a main effect of treatment on relative liver mass where offspring from EX dams had reduced (P = 0.04) liver size compared to CON (**Table 3.1.**). Blood, kidney, and heart masses were not affected by treatment or sex. However, when expressed relative to EBW, females had greater blood, kidney, and heart weights compared to males (**Table 3.1.**). Lungs and submaxillary lymph glands (kg and kg/kg EBW) were increased in female vs. males. Perirenal fat (g and mg/kg) was increased in males vs females (**Table 3.1.**).

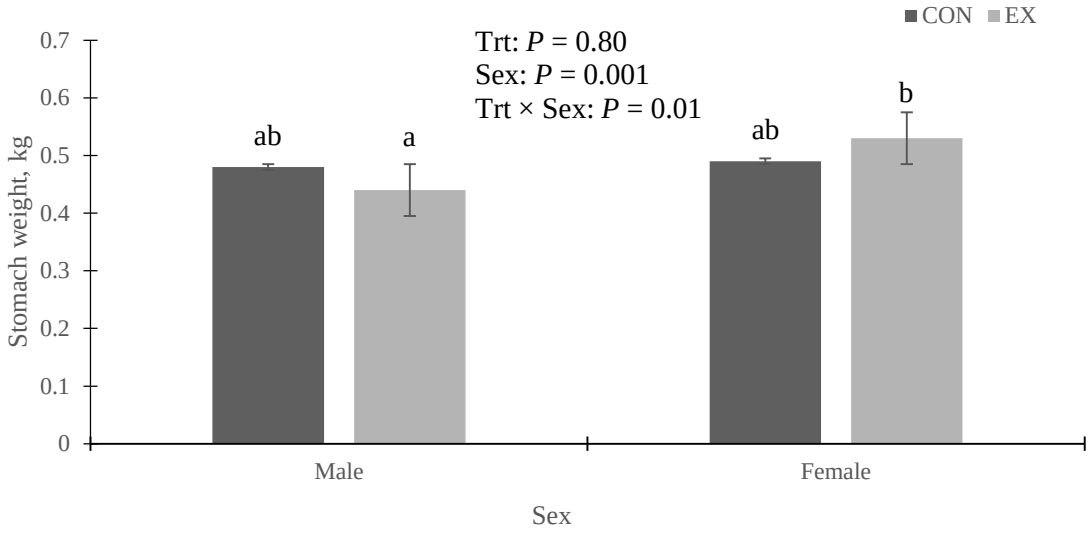
Table 3.1. Organ mass and relative organ mass per empty body weight of pigs born from gilts housed in stalls during gestation (CON) or exercised (EX) per empty body weight (EBW)

	Treatment			Sex			P-values	
Variable	CON	EX	SEM	Female	Male	SEM	Trt	Sex
Body wt, kg	120.5	118.8	1.735	117.8	121.4	1.342	0.71	0.01
EBW[1], kg	117.1	117.2	0.9	116.1	118.2	0.8	0.93	0.08
Blood wt, kg	4.14	4.21	0.14	4.19	4.16	0.11	0.73	0.82
Per EBW, g/kg	35.2	36.1	0.71	36.7	34.6	0.66	0.39	0.02
Heart wt, g	379.9	382.9	12.6	385.2	377.6	9.4	0.87	0.29
Per EBW g/kg	3.24	3.30	0.040	3.38	3.16	0.038	0.29	<0.01
Cardiac fat, g***	101.7	98.0	9.3	114.9	84.9	13.7	0.77	0.17
Per EBW g/kg	0.77	0.83	0.08	0.69	0.91	0.07	0.54	0.03
Lung wt, kg	0.65	0.65	0.02	0.68	0.62	0.02	0.96	0.04
Per EBW, g/kg	5.6	5.6	0.2	5.8	5.2	0.2	0.96	0.02
Spleen wt, g	159.8	153.8	4.8	161.5	152.0	4.5	0.33	0.13
Per EBW g/kg***	1.36	1.31	0.04	1.39	1.28	0.05	0.30	0.05
Liver wt, kg	1.43	1.37	0.06	1.40	1.40	0.05	0.47	0.87
Per EBW, g/kg	12.3	11.4	0.3	12.1	11.6	0.3	0.04	0.25
Pancreas wt, g	172.5	164.4	9.7	158.5	178.3	10.1	0.56	0.15
Per EBW, g/kg***	1.51	1.38	0.051	1.49	1.42	0.048	0.06	0.30
Large intestine wt,	1.30	1.28	0.07	1.18	1.40	0.07	0.80	0.05
Per EBW, g/kg	10.0	11.0	1.0	10.0	11.0	1.0	0.70	0.47
Small intestine wt,	1.11	1.02	0.03	1.00	1.13	0.04	0.10	0.06
Per EBW, g/kg***	9.86	8.79	0.20	9.87	8.79	0.20	<0.01	<0.01
Kidney, g	341.0	349.9	11.3	341.9	348.9	12.5	0.58	0.69
Per EBW, g/kg	2.94	2.99	0.06	3.05	2.88	0.06	0.50	0.04
Lymph glands, g	131.75	135.43	16.31	157.55	109.62	13.40	0.87	<0.01
Per EBW, g/kg	1.11	1.17	0.09	1.33	0.95	0.09	0.63	<0.01
Perirenal fat, g	1.03	1.01	0.06	0.87	1.17	0.05	0.77	<0.01
Per EBW, mg/kg	8.8	8.6	0.40	7.6	9.9	0.40	0.74	<0.01

All interactive P-values were greater than 0.15 with the exception of variable marked with *** which can be found in the following figures: Figure 7: Cardiac Fat; Figure 8: Spleen; Figure 9: Pancreas; Figure 10: Small intestine

[1]EBW: Empty Body Weight, kg

A.



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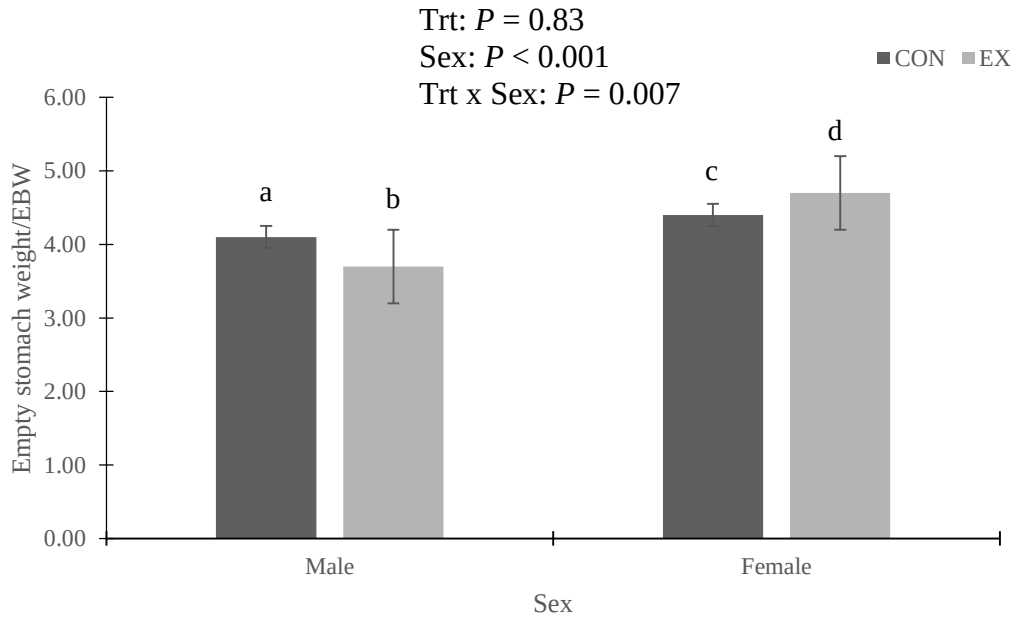
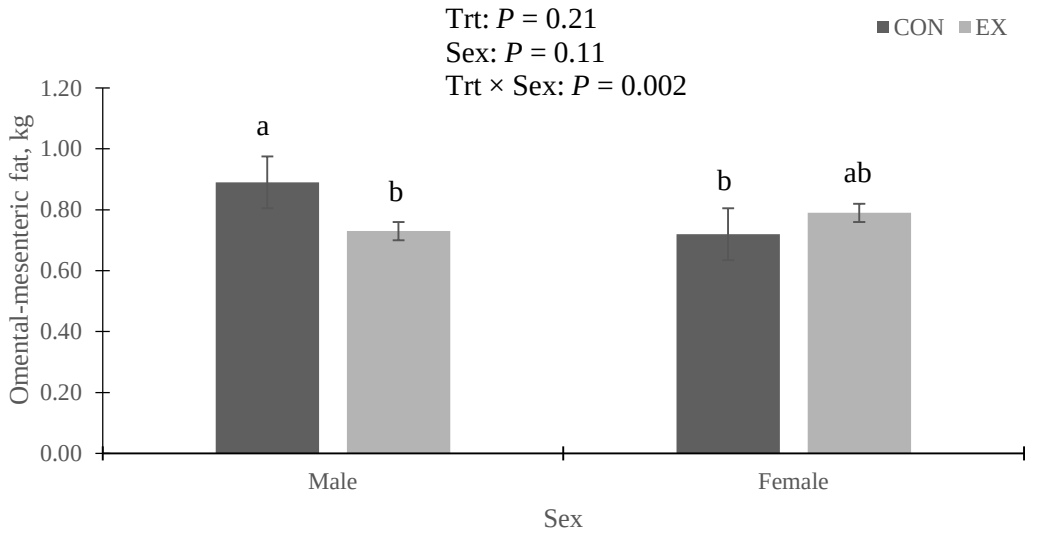


Figure 3.5. Stomach weight of all male and female offspring from gilts housed in stalls during gestation (CON) or exercised (EX) (A). Stomach weight measured relative to empty body weight. (B)

A.



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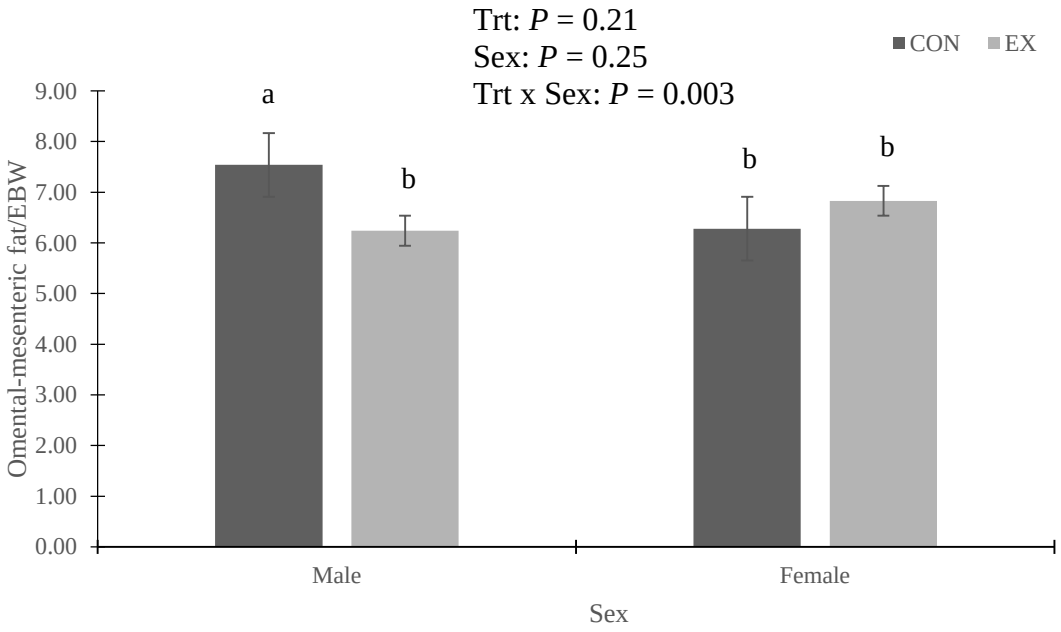

Figure 3.6. Omental-mesenteric fat of male and female offspring from gilts housed in stalls during gestation (CON) or exercised (EX) (A). Relative omental-mesenteric fat (g) (B). EBW=Empty body weight, (g/kg).

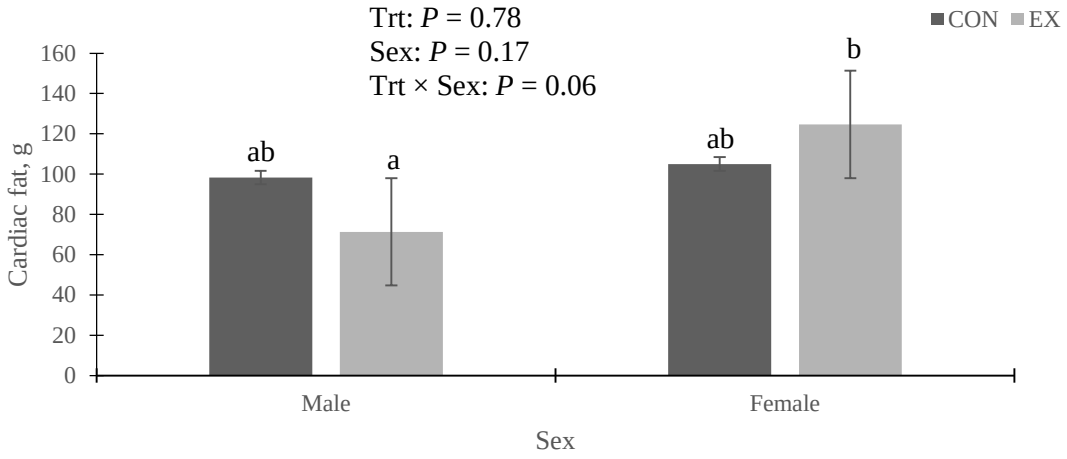

Figure 3.7. Cardiac fat of all male and female offspring from gilts housed in stalls during gestation (CON) or exercised (EX).

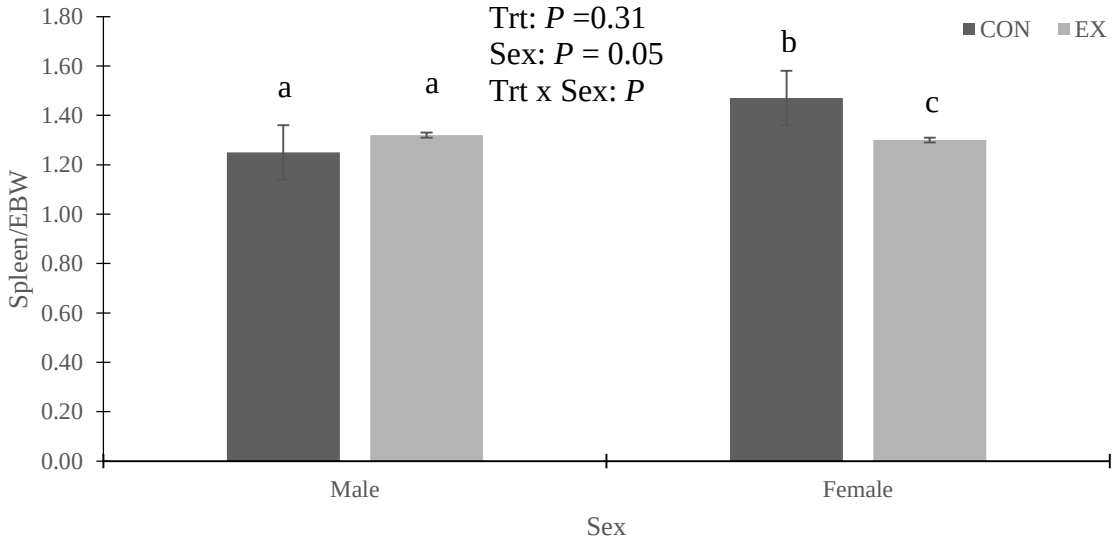

Figure 3.8. Relative spleen mass (g) of male and female offspring from gilts housed in stalls during gestation (CON) or exercised (EX). EBW=Empty body weight, (g/kg).

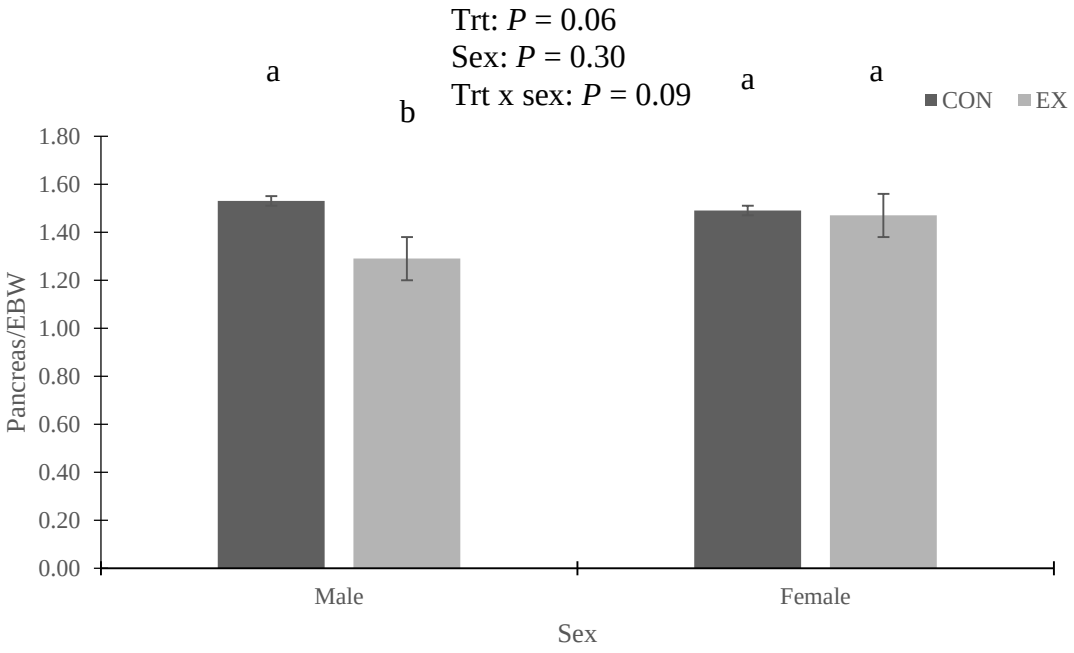

Figure 3.9. Relative pancreas mass (g) of male and female offspring from gilts housed in stalls during gestation (CON) or exercised (EX). EBW=Empty body weight, (g/kg).

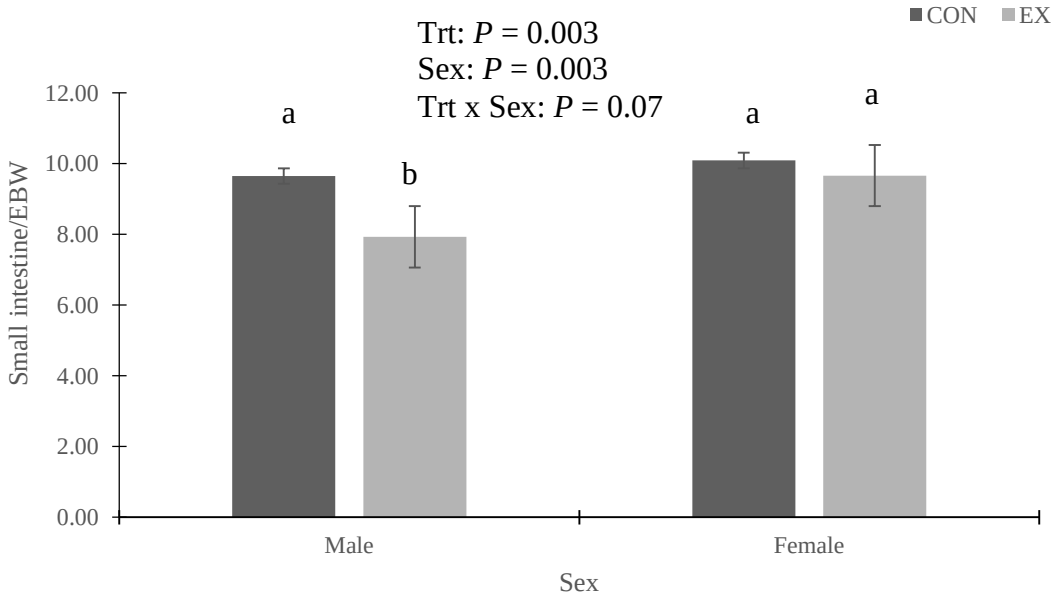

Figure 3.10. Relative small intestine mass (g) of male and female offspring from gilts housed in stalls during gestation (CON) or exercised (EX). EBW= Empty body weight, (g/kg).

Carcass measurements

There was no treatment by sex interaction, or main effect of treatment or sex, ($P \geq 0.15$) for day of age at slaughter. There was no treatment by sex interaction seen for hot carcass weight (kg). While treatment did not impact hot carcass weight, there was a main effect of sex ($P < 0.01$)

Table 3.2. Carcass measurements of pigs from gilts housed in stalls during gestation (CON) or exercised (EX) three times per week for 30 min from d 40 to 104 of gestation.

	Treatment			Sex			P-Value	
Variable	CON	EX	SEM	Male	Female	SEM	Trt	Sex
Age, days	169.3	171.4	2.0	168.9	171.8	2.3	0.46	0.41
Hot carcass weight, kg	91.02	90.35	1.16	92.26	89.11	0.92	0.72	<0.01
Blood lactate, mmol/L	6.99	5.49	0.72	6.35	6.13	0.66	0.11	0.81
Longissimus muscle area, cm^2	59.23	57.55	0.26	57.03	59.68	0.21	0.47	0.09
10^{th} Rib backfat, cm^2	3.48	3.61	0.03	4.19	2.97	0.02	0.60	<0.01
L*	55.73	52.41	0.74	55.25	52.87	0.67	0.001	0.01
b*	5.71	5.29	0.21	5.78	5.22	0.19	0.12	0.03
a*	20.28	20.78	0.29	20.50	20.57	0.27	0.19	0.83
Japanese Color Score,	3.17	6.57	0.13	3.20	3.55	0.12	0.07	0.04
45 minute temp, ℃	41.33	40.46	0.20	40.94	40.85	0.18	<0.01	0.71
24 hour pH	5.27	5.36	0.03	5.37	5.26	0.05	0.05	0.17
Last rib fat, cm	2.29	2.49	0.04	2.59	2.18	0.03	0.15	<0.01
First rib fat, cm	3.63	3.71	0.05	3.89	3.45	0.04	0.68	<0.01
Drip loss, %	6.31	4.54	0.47	6.11	4.74	0.43	<0.01	0.02
Spare rib, kg	3.26	3.08	0.11	3.08	3.26	0.09	0.26	0.10
Semitendinosus, kg	1.33	1.25	0.03	1.25	1.33	0.03	0.09	0.08
Semitendinosus circumference, cm	24.00	23.59	0.39	23.28	24.31	0.35	0.42	0.03
Quadriceps, kg	3.34	3.29	0.10	3.11	3.52	0.13	0.73	0.05
Ham trimmings, kg	1.30	1.45	0.15	1.55	1.20	0.15	0.47	0.09

All interactive P-values were greater than 0.15

with males having heavier carcasses than females (**Table 3.2.**).

The only significant treatment by sex interaction that was found in the carcass measurements was for 45 minute pH ($P = 0.03$). Males from EX dams had greater pH compared to males from CON (**Figure 3.11.**). Females from CON and EX did not differ in pH, but both were greater when compared to males from CON (**Figure 3.11.**). There was a tendency for

several treatment by sex interactions. There was a tendency (P = 0.07) for a treatment by sex interaction for bicep femoris weight where females had greater weight compared to males from CON dams (**Figure 3.12.**). There was a tendency for a treatment by sex interaction (P = 0.10) for NPPC color marbling score with males from CON having a lower score than males from EX and females from CON dams (**Figure 3.13.**). There was a tendency for a treatment by sex interaction (P = 0.08) for ham flank weight where female had greater ham flank weight than males from EX dams (**Figure 3.14.**).

For carcass measurements, effects of treatment were reported for L*, 45 minute temperature, twenty-four hour pH and drip loss percentage (**Table 3.2.**). L star was decreased (P = 0.001) in pigs from EX vs CON as well as greater in males versus females (P = 0.01). Pigs from EX had decreased (P < 0.01) 45-minute temperature compared to CON with no effect (P > 0.71) of sex. While sex did not impact 24 h pH, pigs from EX dams had a greater (P = 0.05) 24 h pH compared to CON. Drip loss percentage was less in (P < 0.01) EX vs. CON. Moreover, males experienced a greater (P = 0.02) drip loss than females. Semitendinosus muscle weight tended to be different with CON having a greater (P = 0.09) semitendinosus muscle weight than EX. Males had greater (P < 0.03) values for tenth rib backfat, first rib fat, last rib fat, b* and L* (**Table 3.2.**). Females had greater (P = 0.04) Japanese color score than males with a tendency (P = 0.07) for EX to be greater than CON (**Table 3.2.**). Semitendinosus circumference and quadriceps weight were greater (P ≤ 0.05) in females compared to males. Females also tended (P ≤ 0.10) to have greater values for LEA, spare rib weight, and semitendinosus weight than males. Males tended (P = 0.09) to have heavier ham trimmings than females (**Table 3.2.**).

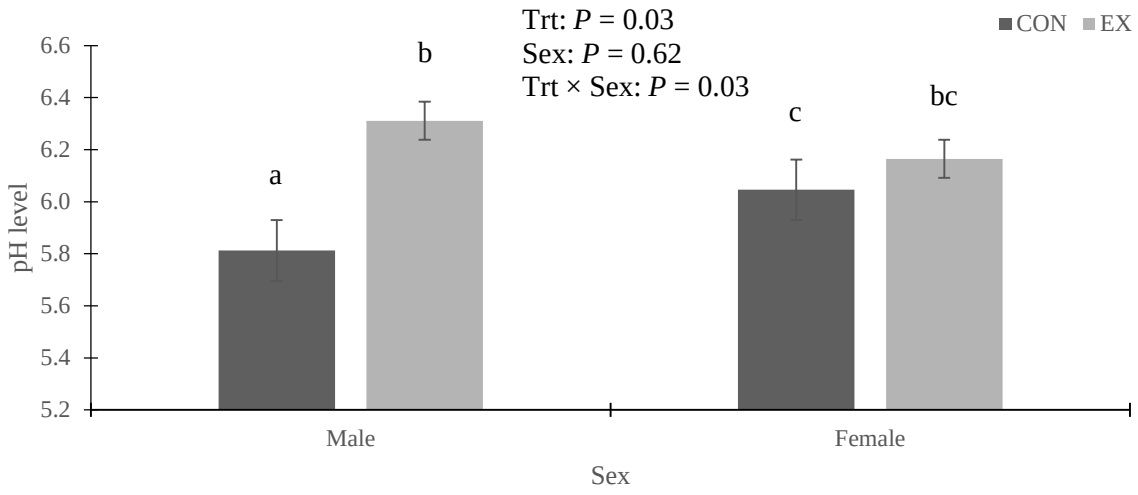

Figure 3.11. 45 minute pH of male and female offspring from gilts housed in stalls (CON) or exercised (EX) during gestation.

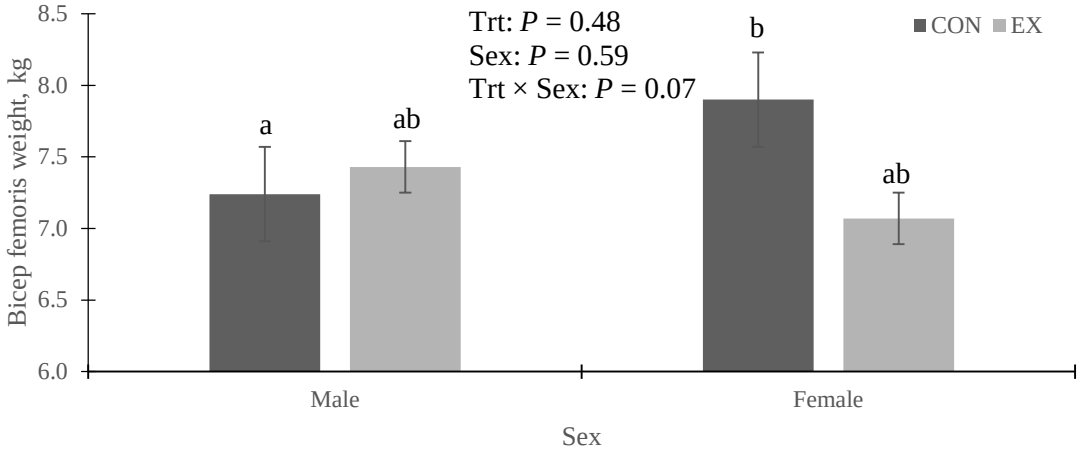

Figure 3.12. Bicep femoris weight of male and female offspring from gilts housed in stalls (CON) or exercised (EX) during gestation.

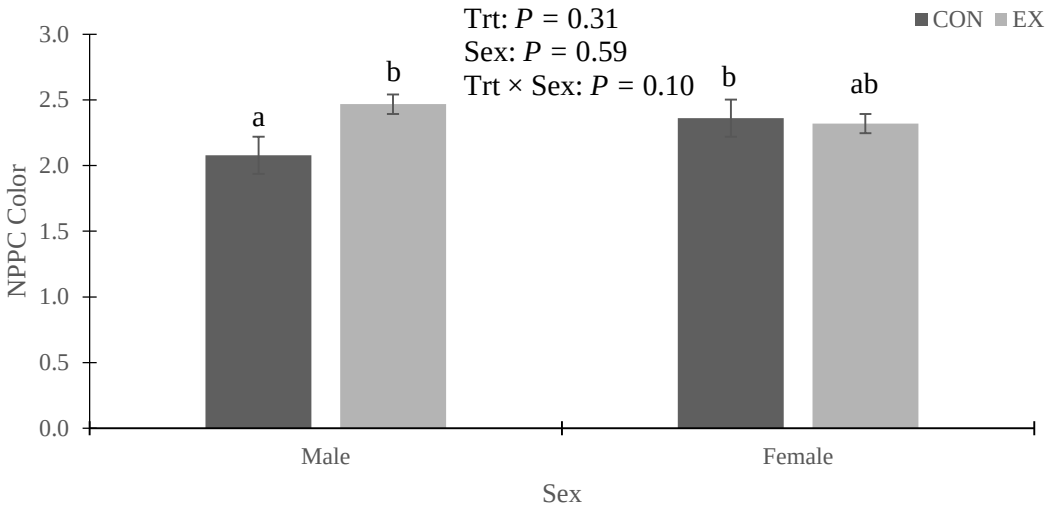

Figure 3.13. National Pork Producers Council color marbling score of male and female offspring from gilts housed in stalls (CON) or exercised (EX) during gestation.

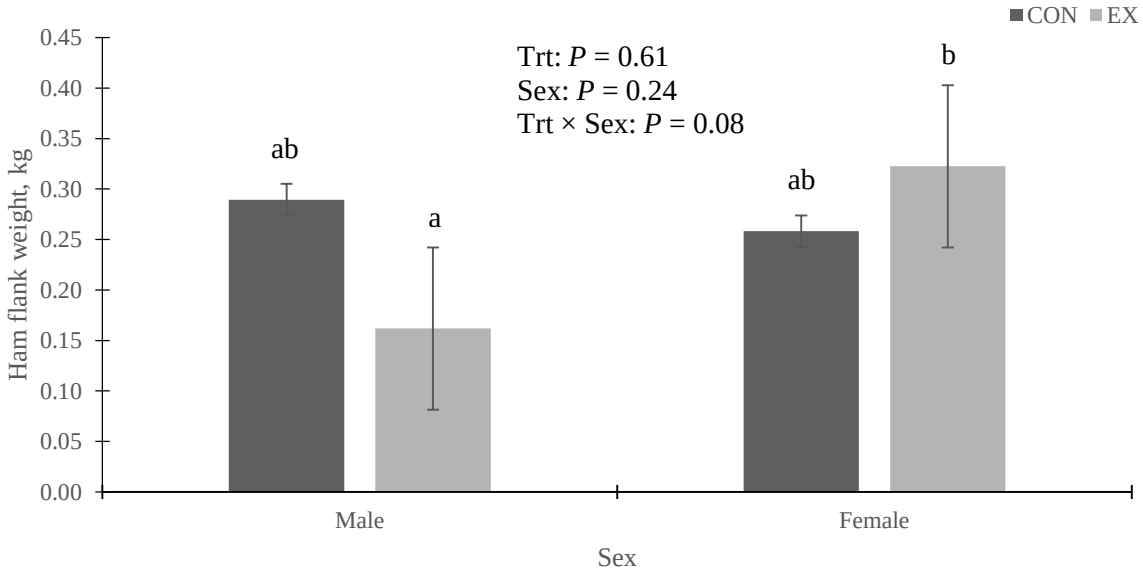

Figure 3.14. Ham flank weight of male and female offspring from gilts housed in stalls (CON) or exercised (EX) during gestation.

Discussion

We believe there is evidence to support that postnatal growth and carcass quality can be impacted by exercise during gestation. In previously reported data from our lab it was shown that exercising gilts during gestation three times per week increased umbilical blood flow compared to the control animals who were housed in traditional stalls. This increase in umbilical blood flow has the potential for increased nutrient transport, metabolic transfer and circulation of hormones (Bell et al., 1983; Harris et al., 2013). The impact of these opportunities afforded to the offspring through improved blood flow during gestation on later life has not been greatly examined. Overall uterine blood flow has been highly correlated to litter size and fetal weight (Hard and Anderson, 1982a). It has been stated that lighter birth weight in piglets has been associated with greater prewean mortality, slower growth rates and decreased pork quality (Herpin et al., 2002; Quiniou et al., 2002; Rehfeldt et al., 2008). The purpose of this study was to relate the effects of exercise and increased umbilical blood flow to the slaughter outcomes of the offspring. It was reported that there were no differences in weaning weight or number weaned (Harris et al., 2013). However, we may be influencing carcass quality and composition prior to weaning and potentially prior to birth. The secondary muscle fibers can greatly contribute to meat quality and are affected by the uterine environment with the total number of fibers being fixed at birth and can greatly impact postnatal growth (Wu et al., 2006). Following these offspring through to slaughter for this portion of the study revealed no effect of treatment on weight at slaughter or day of age at slaughter. There are many components that go into calculating meat quality of pork including color, firmness or wetness and marbling. From the present study the results of most interest in terms of meat quality are 45 minute temperature, 24 hour pH, L* and drip loss percentage. Results from this study showed EX animals having a

significantly lower 45 minute temperature than CON. Another notable measurement obtained from this present study is the 24 hour pH score of the CON versus EX animals. EX animals had a significantly higher pH score at twenty-four hours postmortem than CON. It has been reported that in muscles that become PSE (pale, soft and exudative), the pH decline is twice as fast as in normal muscle (Bendall et al. 1963). Under such conditions of lowered pH and increased temperature the myosin denatures and shrinks, causing a reduction of the filament spacing (Offer and Knight, 1989), causing water to be expelled from the cells and lost, and leading to the measurement of drip loss. Drip loss can be equated to a lower water holding capacity and less tenderness scores in pigs, both of which greatly contribute to meat quality aspects (Rehfeldt and Kuhn, 2006). Pork with a very low water holding capacity often exhibits a very coarse open texture that leads to excessive fluid loss and can result in poor meat quality upon cooking (NPPC, 2000). Low water-holding capacity in PSE pork has been shown to be the consequence of a fast pH decline, resulting in the combination of a low pH and a high temperature post-mortem (Solomon et al., 1998). Both drip loss percentage and pH level can be used to determine the chance of PSE pork. In a study conducted by Rehfeldt et al. (2008), there was a reported tendency for greater drip loss in light weight pigs (1.08 ± 0.01 kg) as well as an increased percentage of intramuscular fat for light weight pigs. The results of this current study showed that offspring from EX gilts had a decreased drip loss percentage compared to control. In terms of color scoring, EX animals had a significantly darker L* than CON animals. This darker L* score would suggest a lower instance of PSE pork for EX animals compared to CON as L* is the main value that changes quality out of the L*a*b* color scale (NPPC, 2000). This data collected regarding meat quality measurements may be suggesting that EX mothers during gestation may help offset the lower meat quality traits of light birth weight piglets as well as combating the

instances of PSE pork on the rail. While it is not completely known all the alterations that increased activity may have caused in our model, we do know that umbilical blood flow was increased, and may be a contributor to the enhanced carcass outcomes that were observed in the present study.

Though there were limited effects of treatment seen on organ mass measurements, there were several effects of sex observed. Agreeable with several other studies, female measurements often varied from male measurements. Males are frequently heavier than females which was a result seen here and grow to reach market weight earlier (White et al., 1995). Females had lighter intestinal tracts possibly leading to fewer or underutilized absorption of nutrients. Numerous labs have reported that females tend to be leaner or have a greater percentage of lean meat than males (Gondret et al. 2006; Rehfeldt et al. 2008). Similar findings were presented here with females having decreased 10^{th} rib backfat, first rib and last rib fat, as well as lower perirenal fat compared to males.

Another further point of interest from this study's findings may be the tendency for a treatment by sex effect on the pancreas. Males from exercised mothers tended to have a lighter weight pancreas than all other groups. There are several functions that the pancreas performs that are essential to the growth of a healthy animal, including digestion and the regulation of blood sugar. Although not statistically different the exercised male weights were closer to the female groups than the control males, potentially supporting the idea that there is a lower nutrient absorption. There may be a positive relationship between body weight gains and weight of the pancreas and the proteolytic enzyme activity of the pancreas (Gorrill and Friend, 1970).

Implications

Numerous studies have demonstrated the effects of maternal treatments can have on offspring, both during gestation and during early postnatal life. Although very few have focused on the effect of housing systems in the swine industry, even less followed the offspring through to harvest. The potential meat quality differences discussed here may be of interest to explore further when considering the design of new gestation facilities. The potential for a reduction in PSE pork without having to add stabilizing product at slaughter is highly encouraging. If an impact on the end product can be made even before birth that could be extremely beneficial to producers overall.

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CHAPTER 4. GENERAL DISCUSSION AND FUTURE DIRECTIONS

The topics discussed in this thesis offer critical insight into a problem that greatly affects today's swine industry. The pork industry has greatly improved production in recent years with gains in litter size, through genetic selection and the introduction of hyper prolific dam lines into commercial production, along with improvements in nutrition, housing and herd health management. However, the impact that low viability piglets have on production systems can be felt from the farrowing house all the way to the processing plant.

The first study discussed in Chapter 2 highlights a potential avenue to impact piglet viability prior to birth through the increase of uterine blood flow. The method we chose to explore was the use of various pharmaceuticals with vasodilating properties, infused directly into the blood stream in hopes of impacting not only overall blood flow but specifically uterine blood flow. There were several drug compounds in this preliminary study which showed potential to accomplish this with one, treatment 48836, being the drug compound suggested for further study. For this preliminary study we utilized non-pregnant crossbred gilts however the next steps in this process would be to infuse the drug compounds into pregnant animals. A pregnant animal's system greatly differs from the non-pregnant system in several ways. As discussed in the literature review in Chapter 1 in order for the maternal body to support pregnancy it needs to undergo numerous physiological changes including a large plasma volume increase, increase in red blood cells, as well as an increase in cardiac output, stroke volume and heart rate (Stocke and Metcalfe, 1994). Although simply administering a drug to a pregnant sow would not be a simple or straight forward as it sounds. There are the numerous changes along different stages of pregnancy to be considered as well as at what time point the administration of a drug compound would have the greatest effect on piglet viability. This preliminary study involved the very

intensive method of directly infusing the drugs into the blood stream of the sow. This however would not be a feasible option in today's sow farms. Further study into potentially administering a drug compound through the feed or water may be needed in order to make this avenue of impacting uterine blood flow possible on the producer level.

An additional method of influencing piglet viability discussed in this thesis was the implementation of exercise during gestation to impact uterine blood flow. In the preliminary study conducted by Harris et al. (2013), there was an increase in umbilical blood flow for fetuses in exercised mothers but no difference in birth weight or weaning weights of the piglets. In order to determine a potential impact of uterine blood flow on meat quality, these offspring were followed to harvest. In Chapter 3 we discussed the data from the slaughter of these pigs. The findings from the slaughter data collected may suggest that meat quality in swine is impacted by exercise of the mother. The animals from the exercised mothers had a decreased ($P < 0.05$) drip loss percentage (6.31 vs 4.54 ± 0.48%), increased ($P \leq 0.05$) pH at 24 hr. (5.36 vs 5.27 ± 0.03) and an increased ($P < 0.05$) L* (55.73 vs 52.40 ± 0.74) all of which contribute to meat quality characteristics. One avenue that was not explored in this experiment and would be beneficial in future projects would be to analyze and assess the muscle fiber number and type both during gestation and postnatal life. Light birth weight piglets have been shown to have fewer muscle fibers (Dwyer et al., 1994) as well as excessive fiber hypertrophy and formation of giant fibers (Fiedler et al., 2004). Muscle fiber number and type can have a great impact on palatability and overall meat quality.

The next steps following this thesis discussion would be to implement the practices discussed in chapters two and three into a production system and measure the outcome of the offspring. However, some challenges may arise including the logistics of administering such

measures on today's sow farms. Chapter 2 involved the use of pharmaceutical compounds with one compound showing the most promise in the non-pregnant animal being treatment 48836. Treatment 48836 had the greatest percent change within a dose, the greatest percent change overall and the highest peak blood flow of all the drug treatments applied. These outcomes make this the drug with the most potential to impact the pregnant sow's uterine blood flow and in turn blood flow to the piglet. Not knowing the exact biochemical makeup makes it difficult to discuss what the best method of administration would be. Regardless, thinking about current production practices, producers are going to want a product that has the least intensive administration with maximal effect. A suggested product would be one that could be fed to the sow rather than an injection or a direct infusion.

The challenge that will be the most difficult to overcome to implement a system as described in Chapter 3 is the fact that the majority of today's production facilities are built with efficiency in mind. This means sows are housed in gestation stalls and most systems do not have the space or the man power to exercise the mothers. Although the results from the project in chapter 3 are interesting in their suggestion of exercise potentially impacting meat quality there will need to be more research with a larger number of dams and their offspring included to establish if exercise during gestation will be a beneficial avenue for the producer to receive the most return on their pigs at the rail.

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APPENDIX

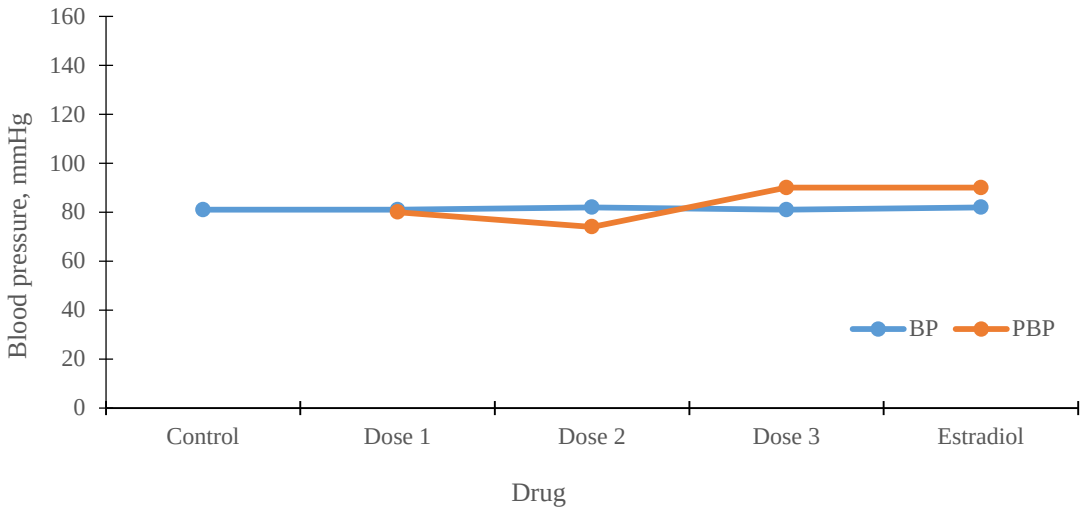

Figure A1. Blood pressure measurements from gilt 31-1 on drug treatment 48836.

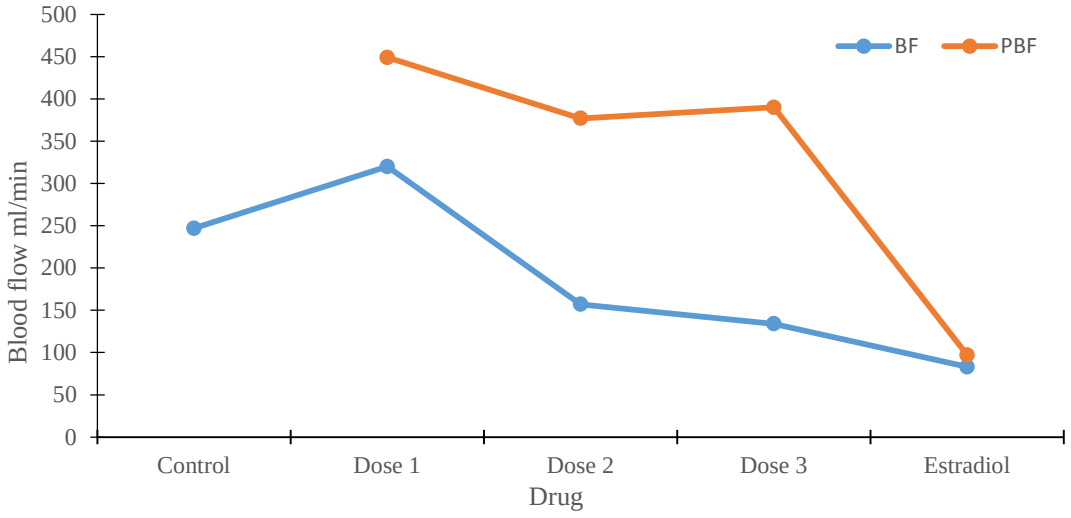

Figure A2. Blood flow measurements from gilt 31-1 on drug treatment 48836.

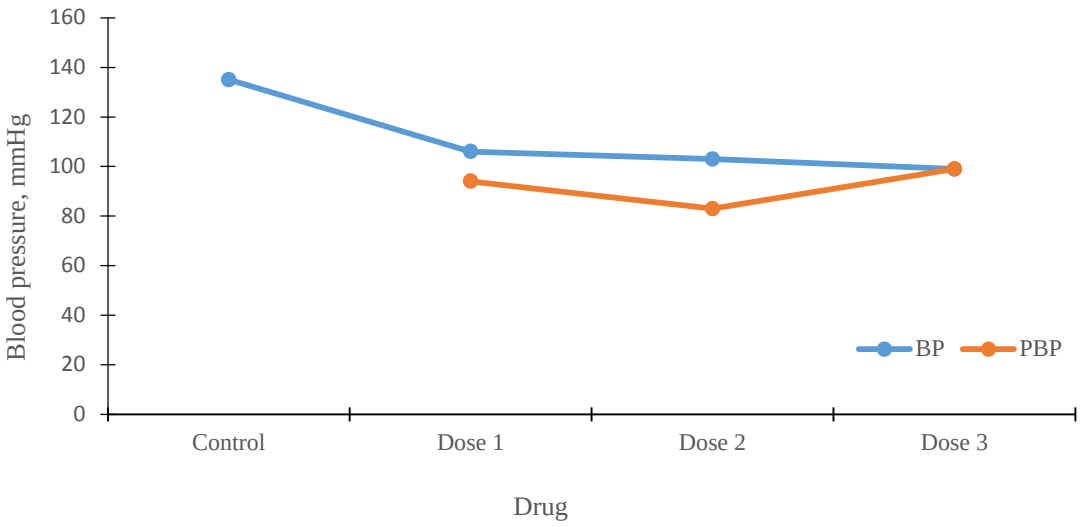

Figure A3. Blood pressure measurements from gilt 1-1 on drug treatment 48836.

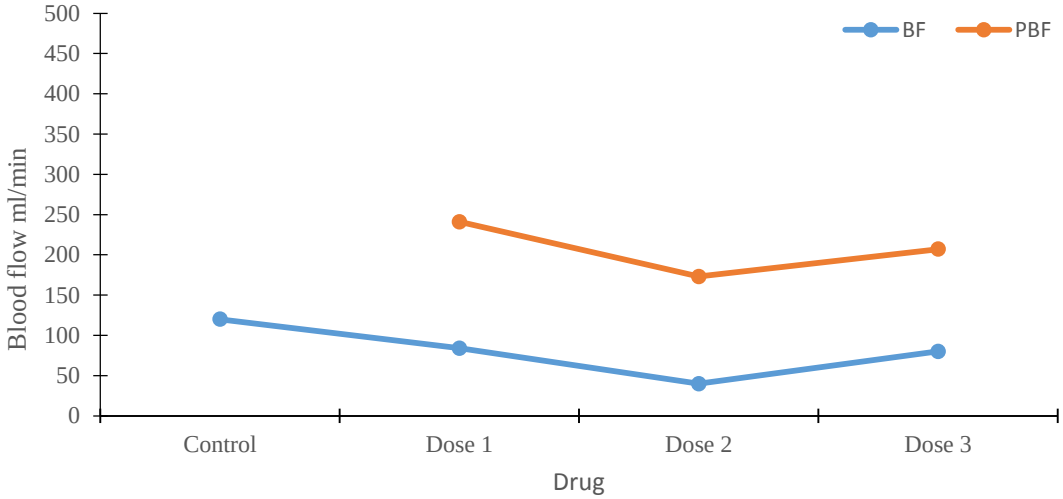

Figure A4. Blood flow measurements from gilt 1-1 on drug treatment 48836.

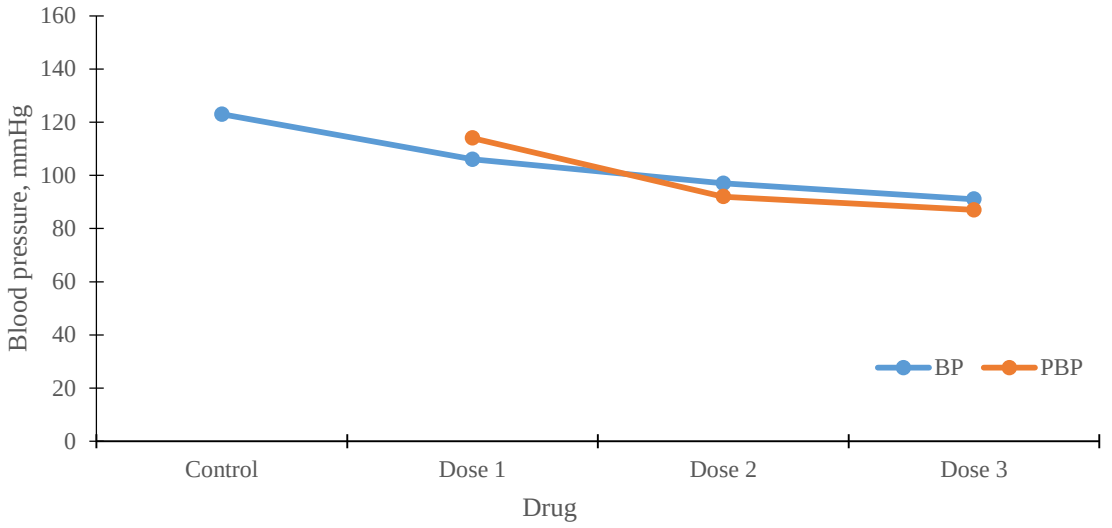

Figure A5. Blood pressure measurements from gilt 26-1 on drug treatment 48836.

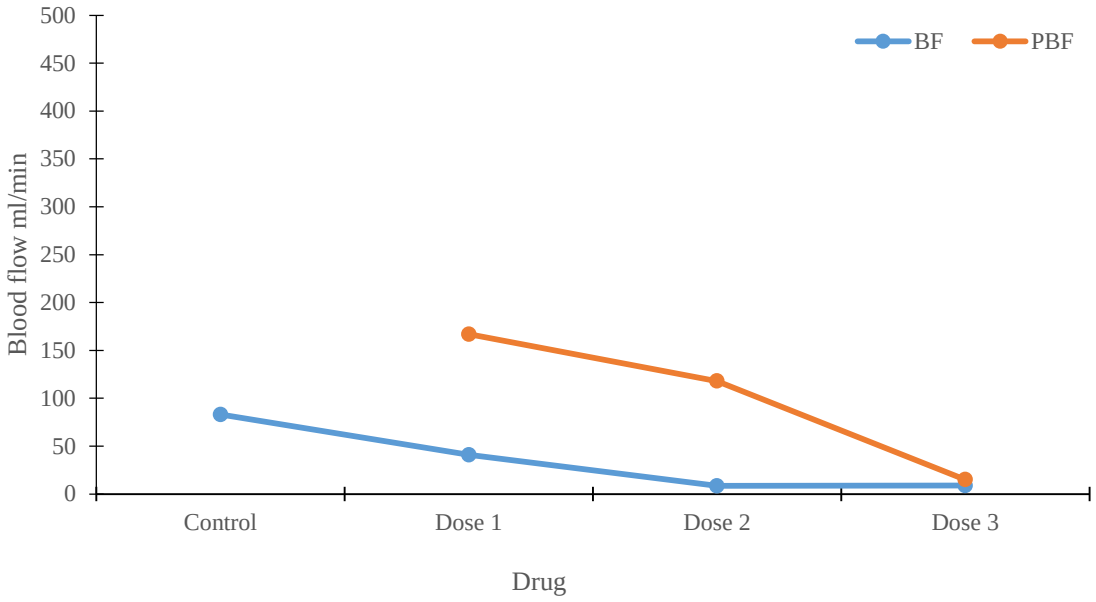

Figure A6. Blood flow measurements from gilt 26-1 on drug treatment 48836.

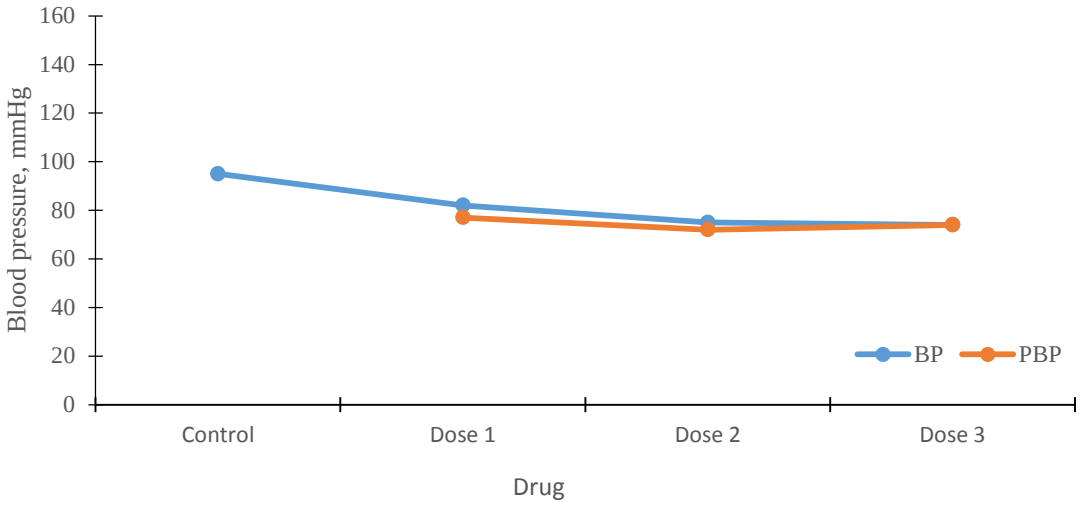

Figure A7. Blood pressure measurements from gilt 31-4 on drug treatment 48836.

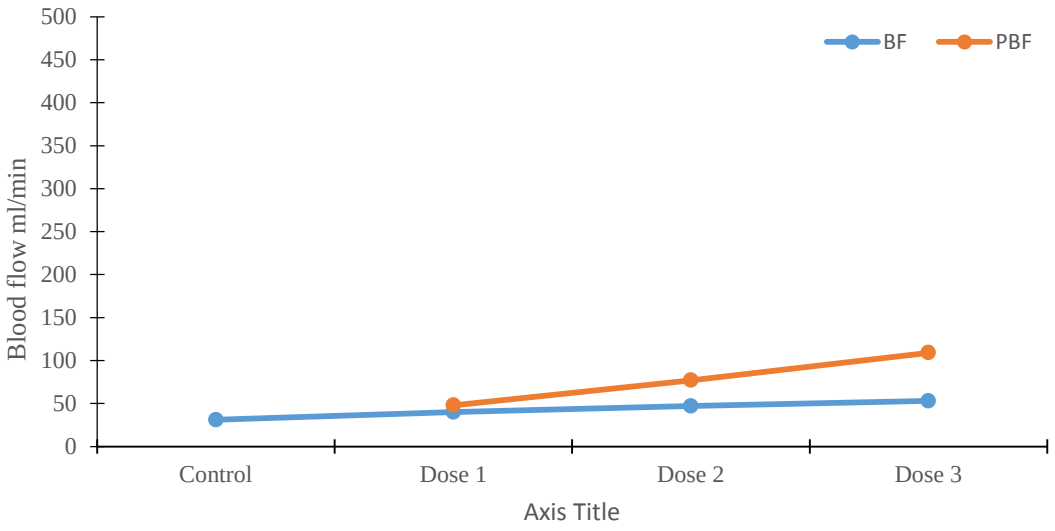

Figure A8. Blood flow measurements from gilt 31-4 on drug treatment 48836.

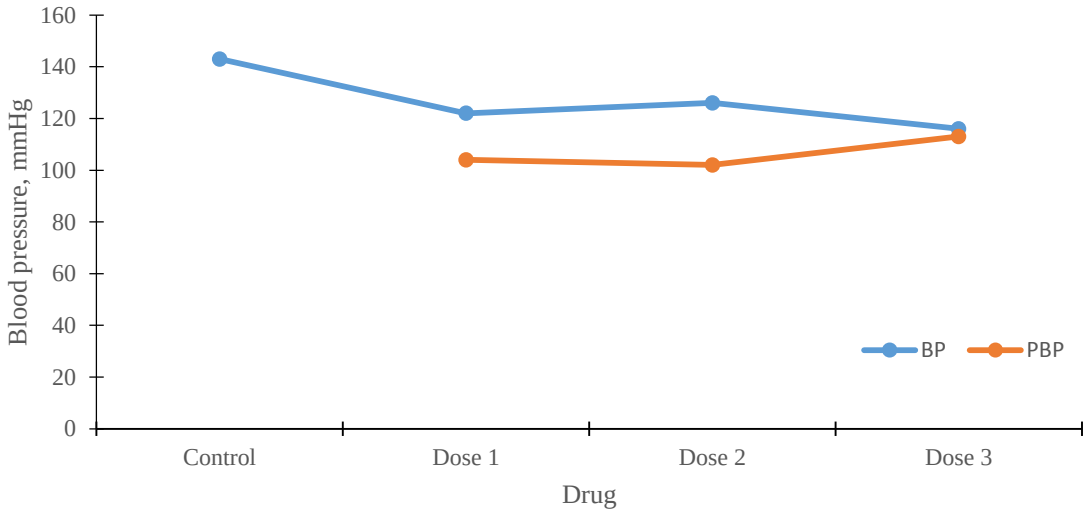

Figure A9. Blood pressure measurements from gilt 33-2 on drug treatment 51625.

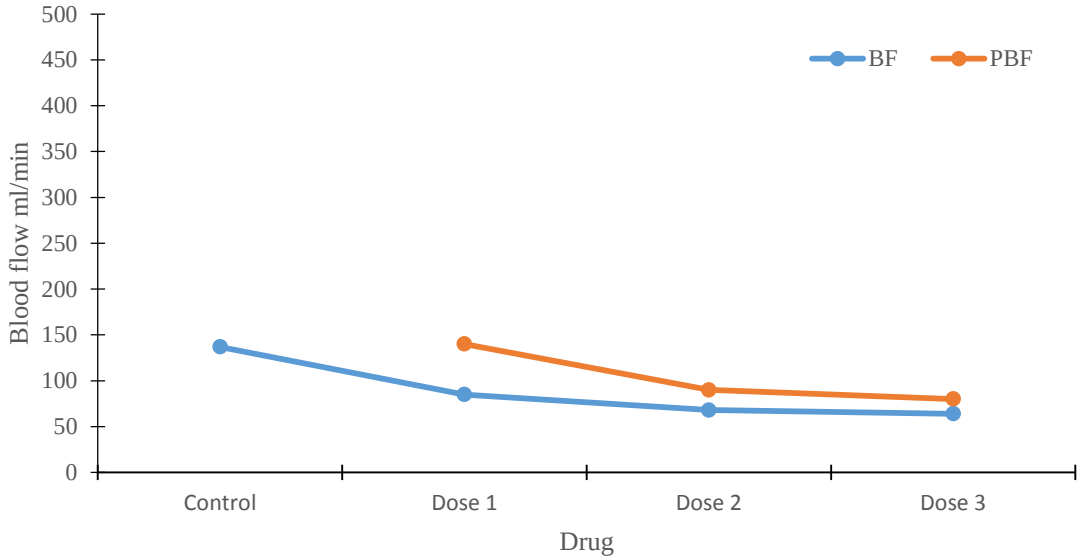

Figure A10. Blood flow measurements from gilt 33-2 on drug treatment 51625.

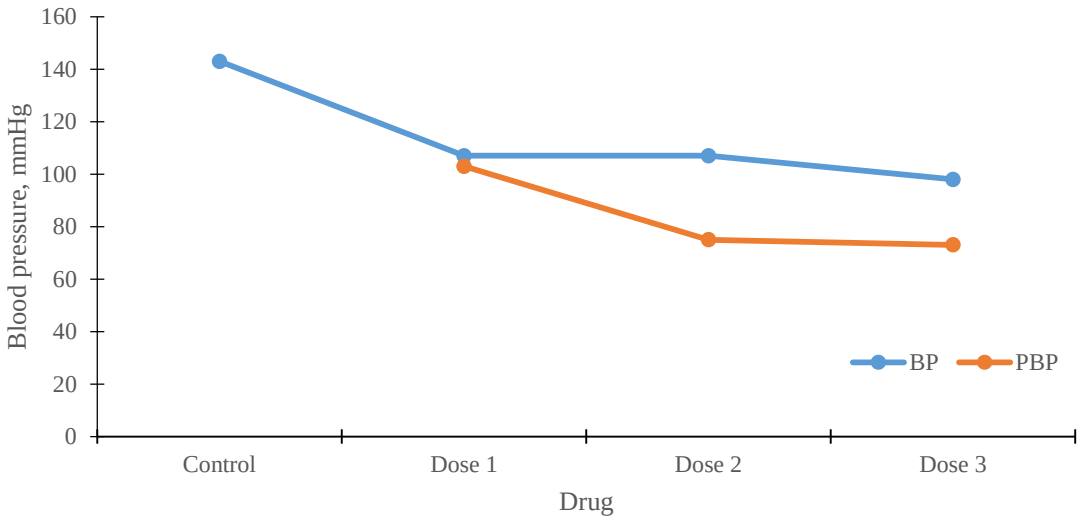

Figure A11. Blood pressure measurements from gilt 36-5 on drug treatment 51625.

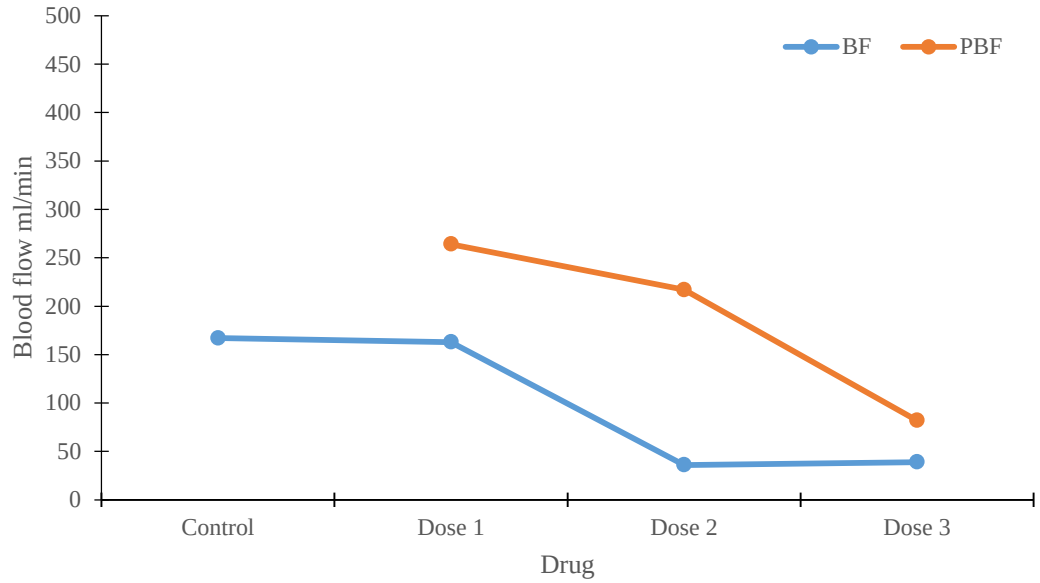

Figure A12. Blood flow measurements from gilt 36-5 on drug treatment 51625.

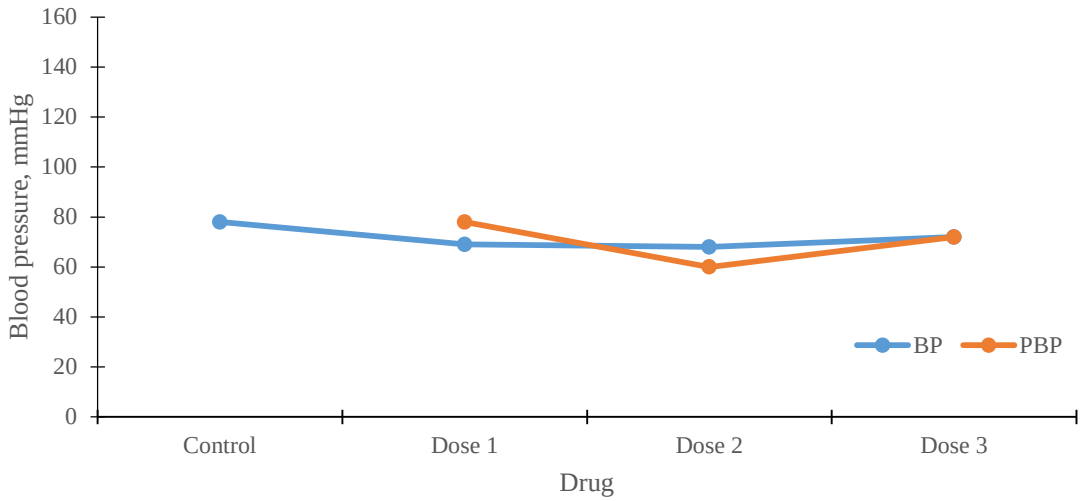

Figure A13. Blood pressure measurements from gilt 33-1 on drug treatment 51625.

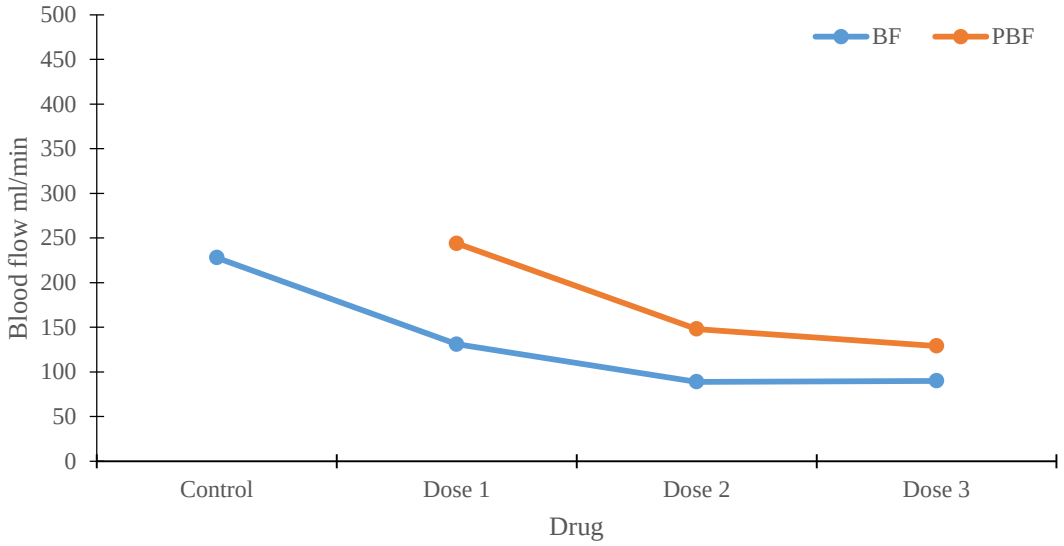

Figure A14. Blood flow measurements from gilt 33-1 on drug treatment 51625.

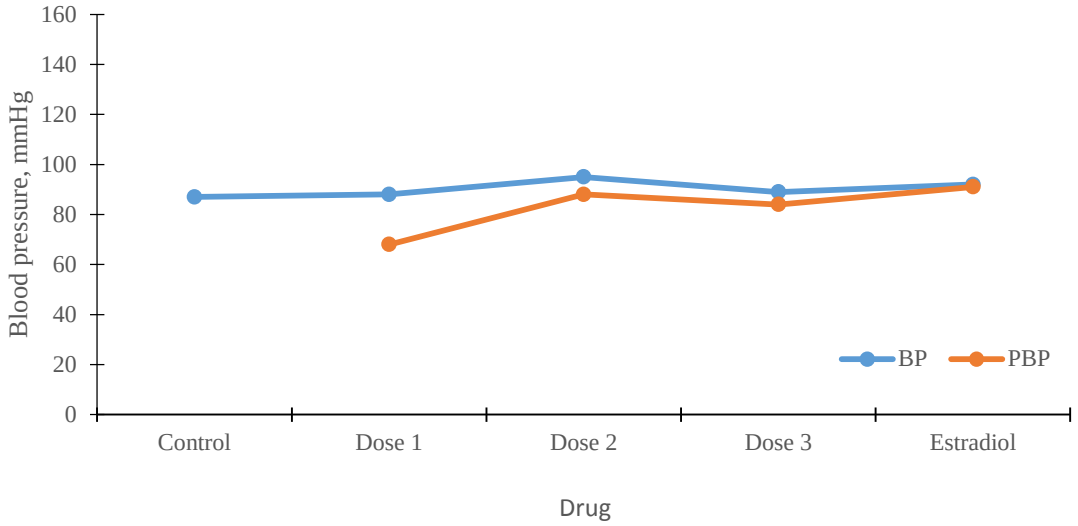

Figure A15. Blood pressure measurements from gilt 36-2 on drug treatment 51625.

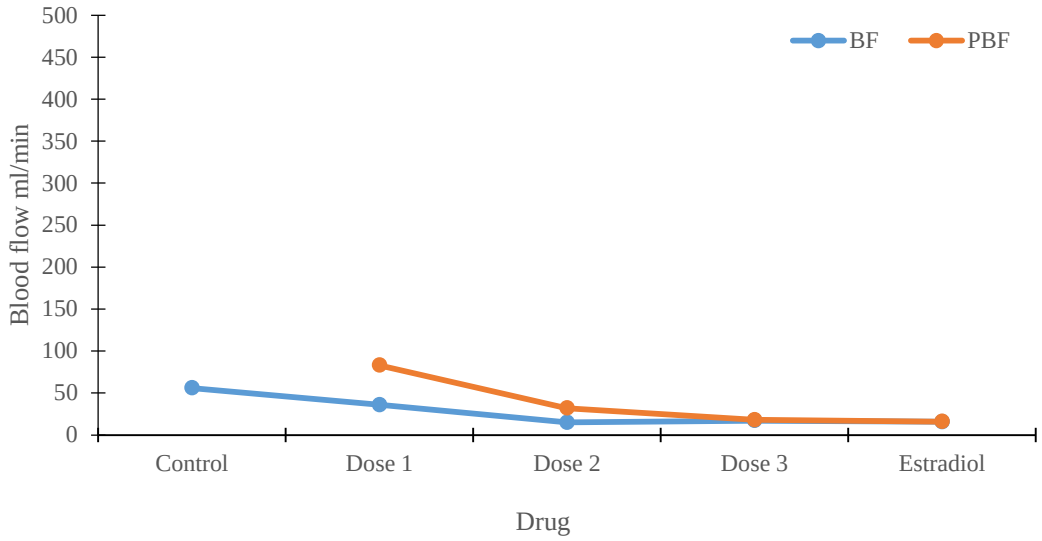

Figure A16. Blood flow measurements from gilt 36-2 on drug treatment 51625.

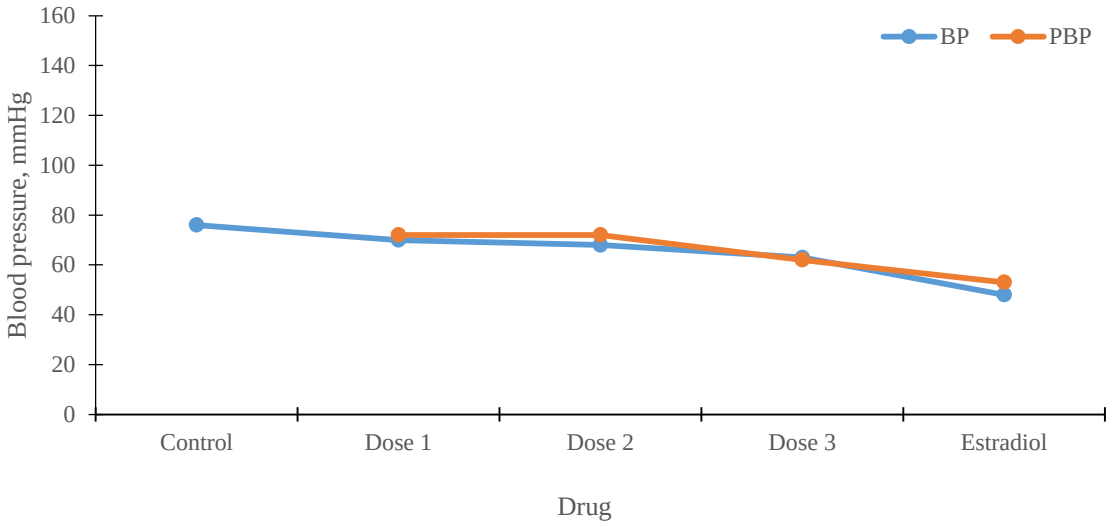

Figure A17. Blood pressure measurements from gilt 34-4 on drug treatment 83187.

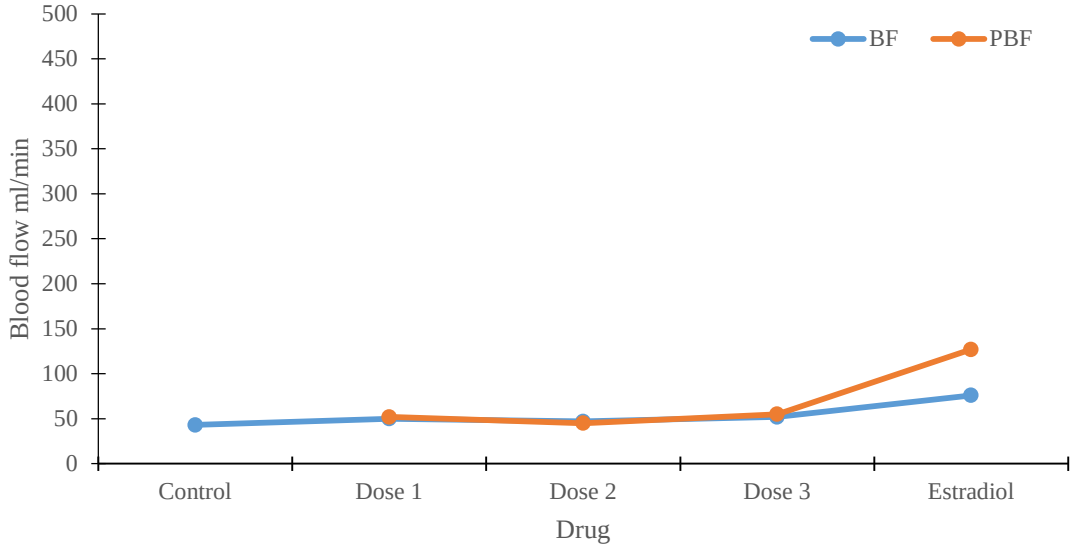

Figure A18. Blood flow measurements from gilt 34-4 on drug treatment 83187.

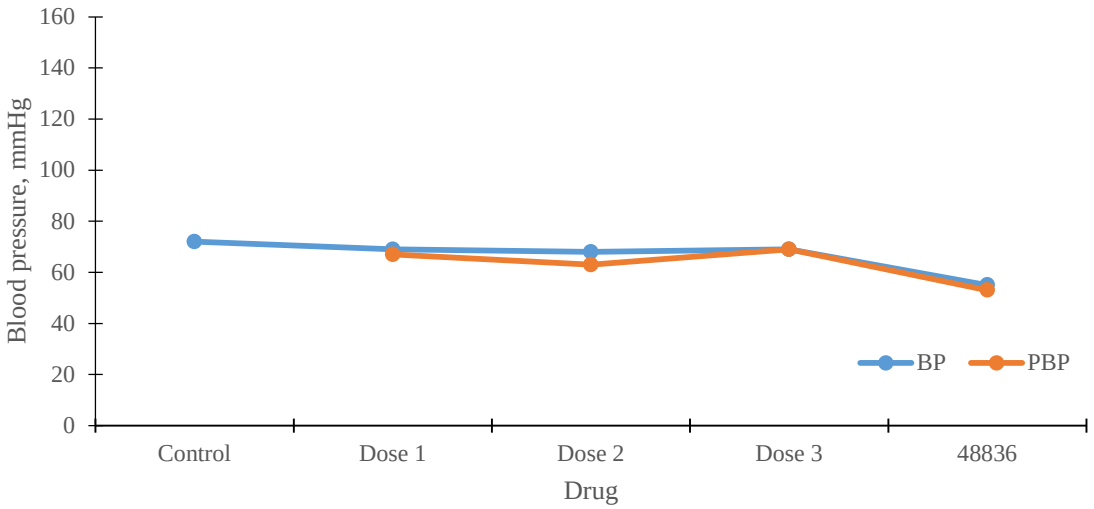

Figure A19. Blood pressure measurements from gilt 26-2 on drug treatment 83187.

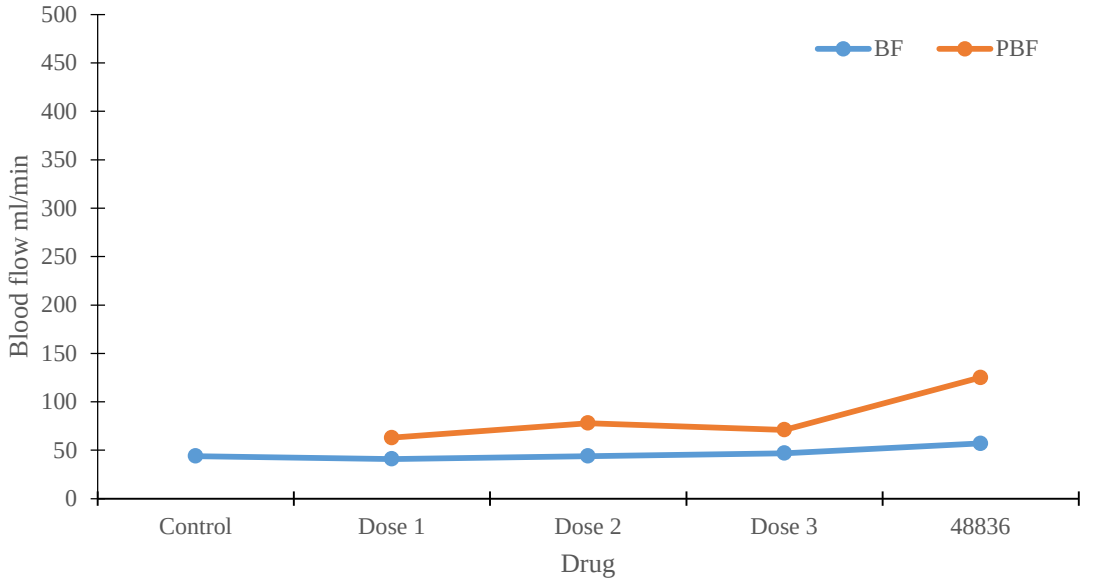

Figure A20. Blood flow measurements from gilt 26-2 on drug treatment 83187.

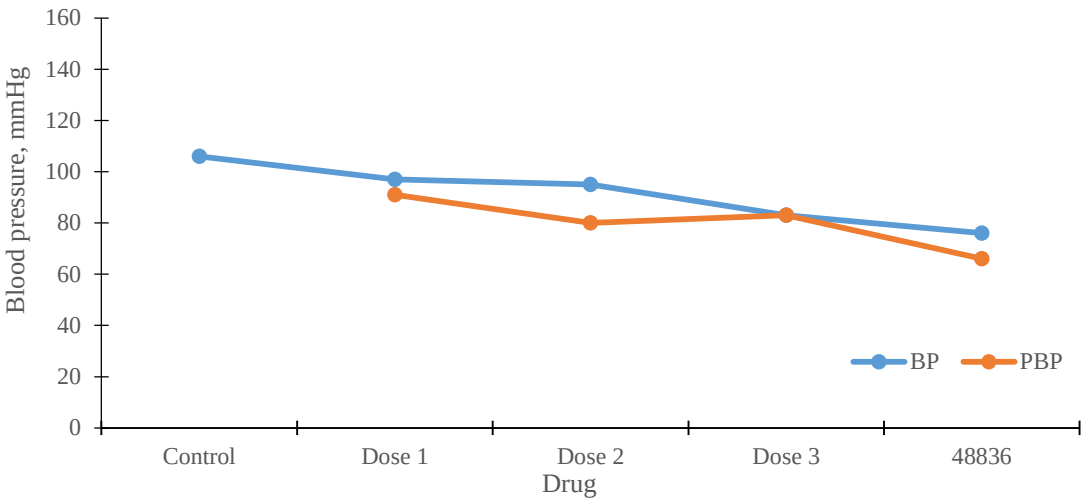

Figure A21. Blood pressure measurements from gilt 35-5 on drug treatment 83187.

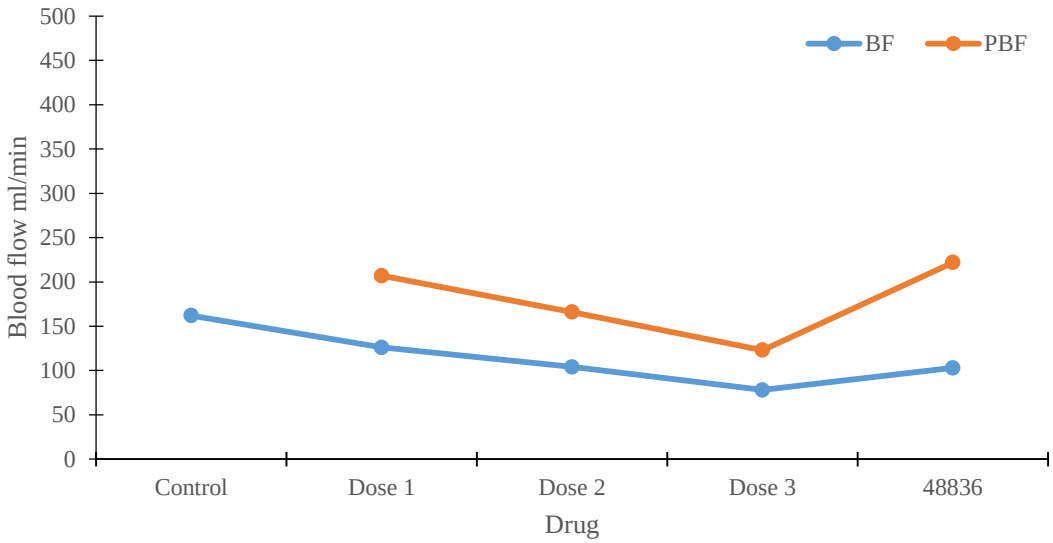

Figure A22. Blood flow measurements from gilt 35-5 on drug treatment 83187.

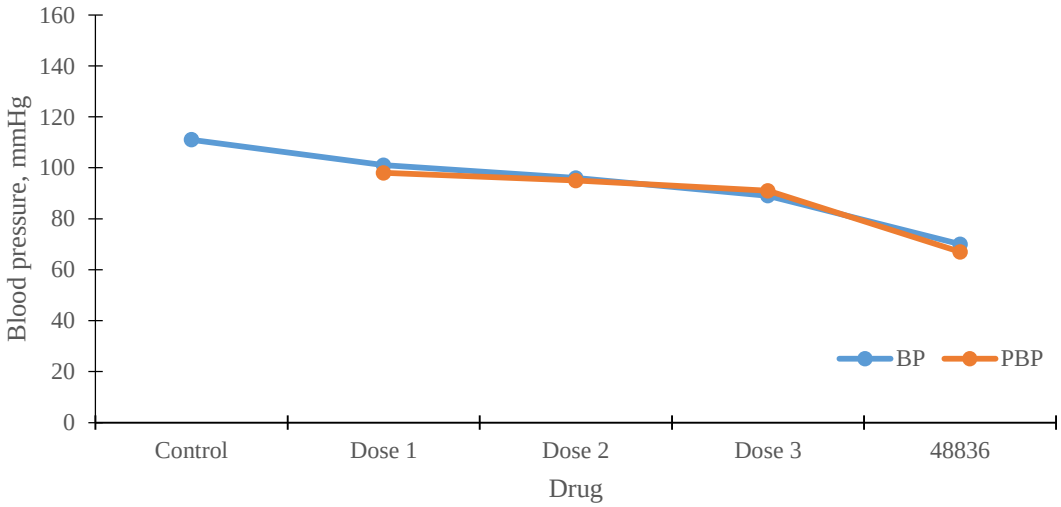

Figure A23. Blood pressure measurements from gilt 36-6 on drug treatment 83187.

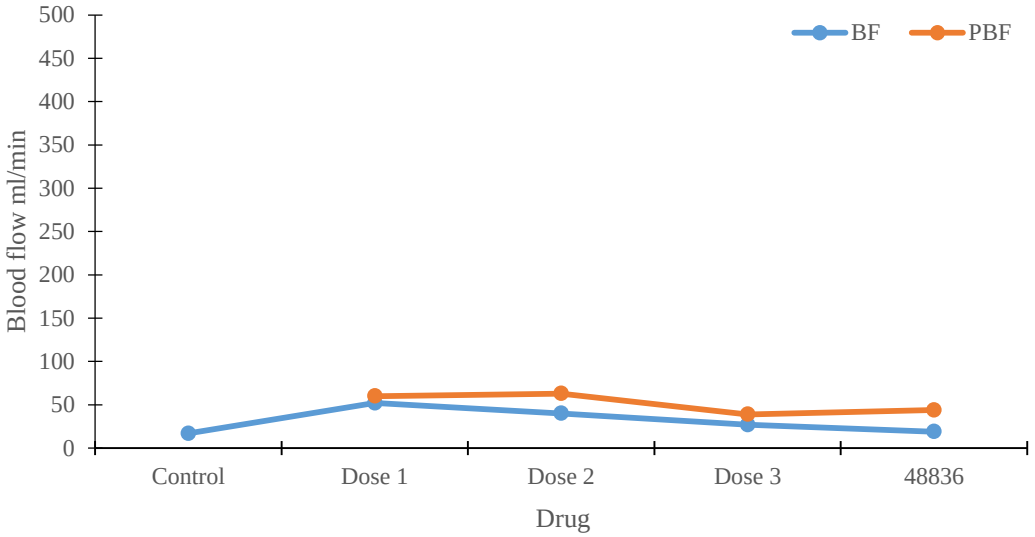

Figure A24. Blood flow measurements from gilt 36-6 on drug treatment 83187.

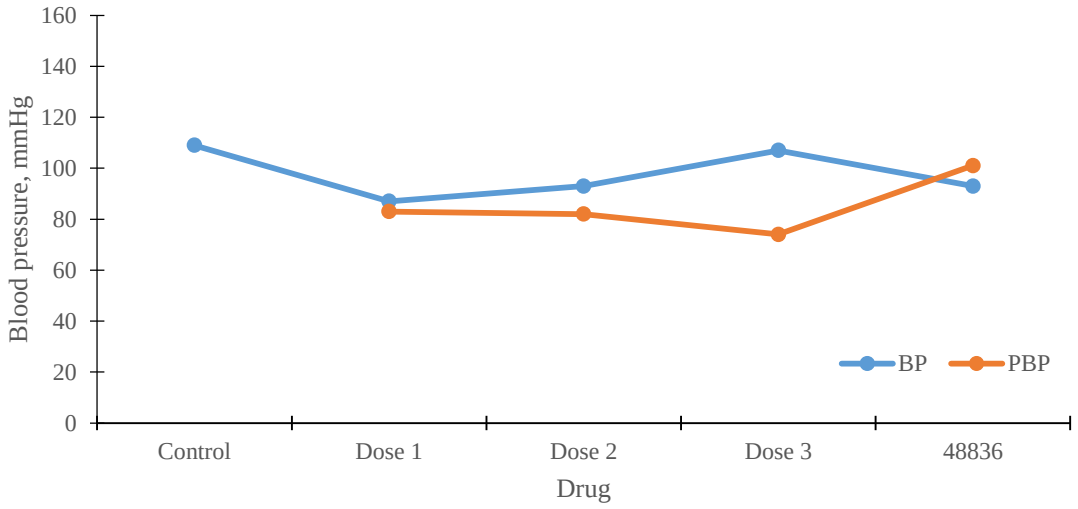

Figure A25. Blood pressure measurements from gilt 34-6 on drug treatment 8165.

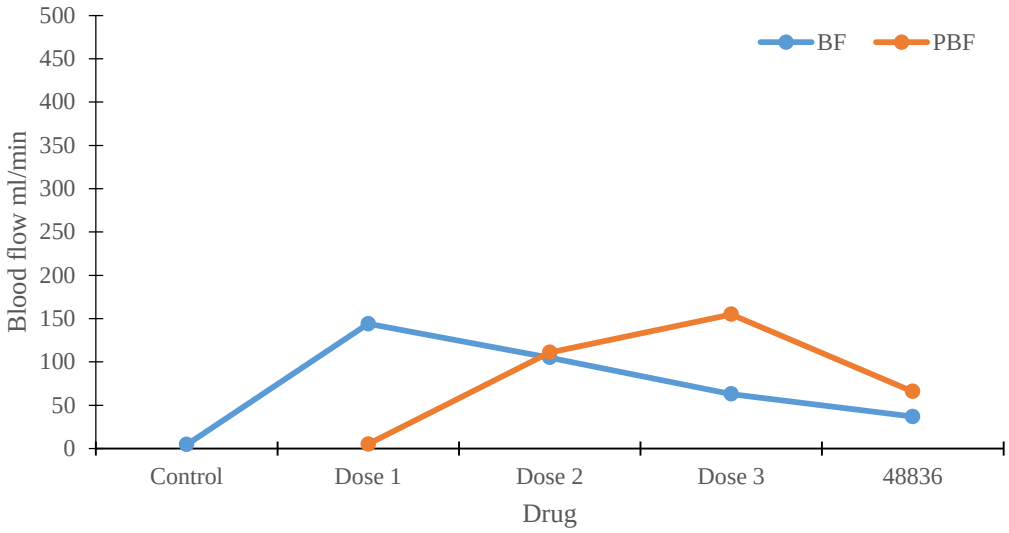

Figure A26. Blood flow measurements from gilt 34-6 on drug treatment 8165.

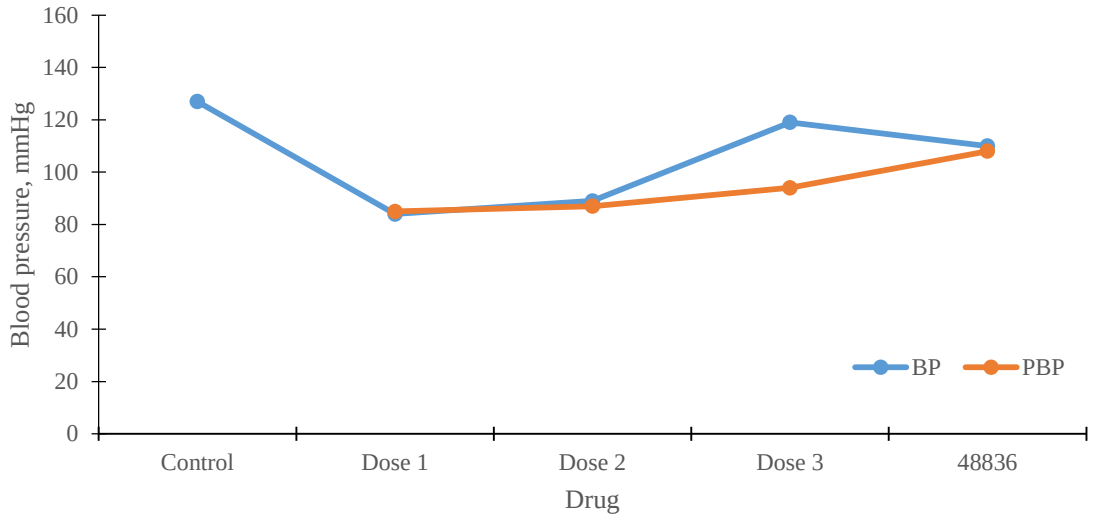

Figure A27. Blood pressure measurements from gilt 19-3 on drug treatment 8165.

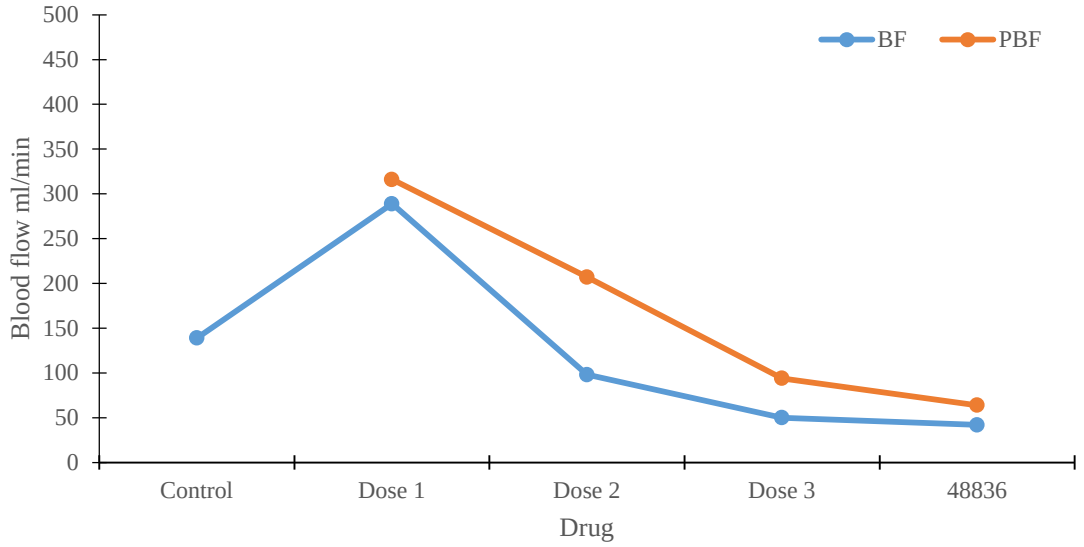

Figure A28. Blood flow measurements from gilt 19-3 on drug treatment 8165.

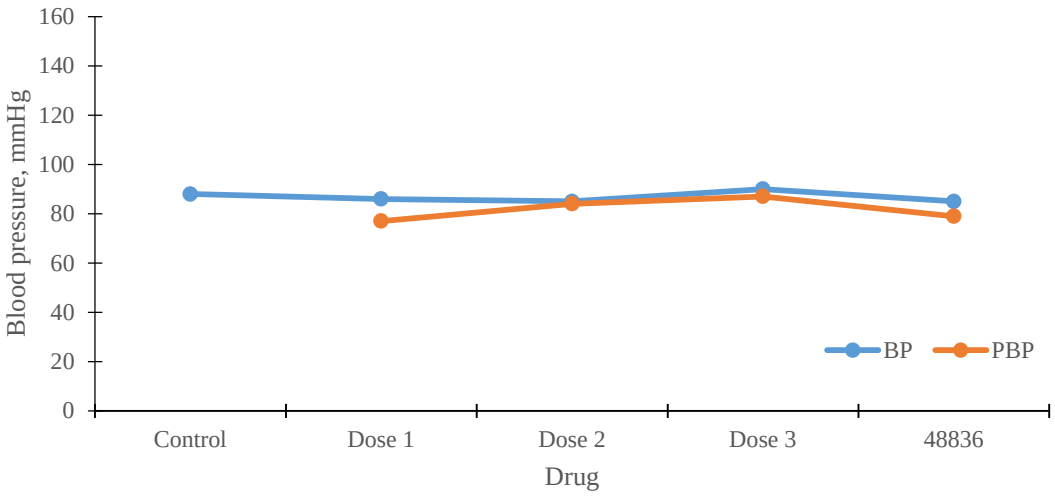

Figure A29. Blood pressure measurements from gilt 43-1 on drug treatment 8165.

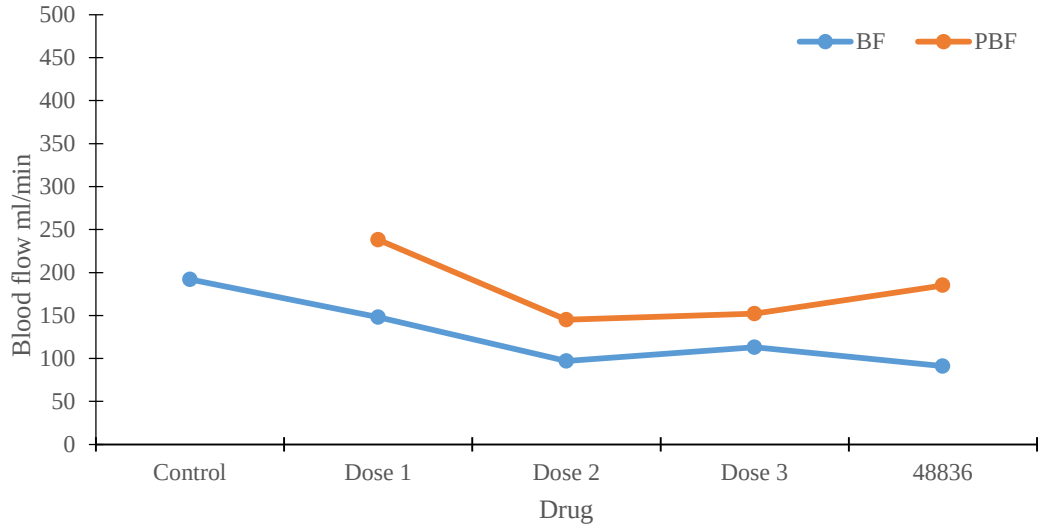

Figure A30. Blood flow measurements from gilt 43-1 on drug treatment 8165.

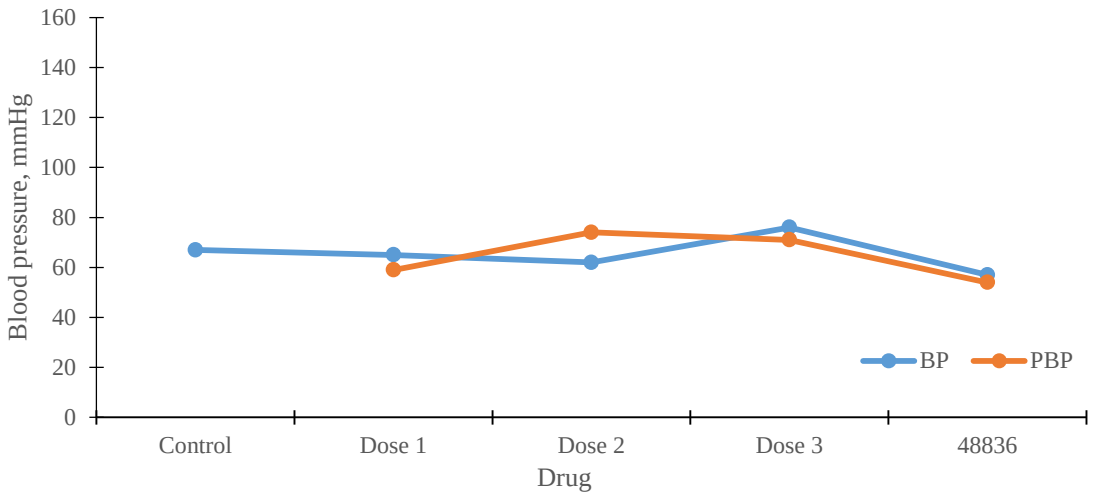

Figure A31. Blood pressure measurements from gilt 39-1 on drug treatment 8165.

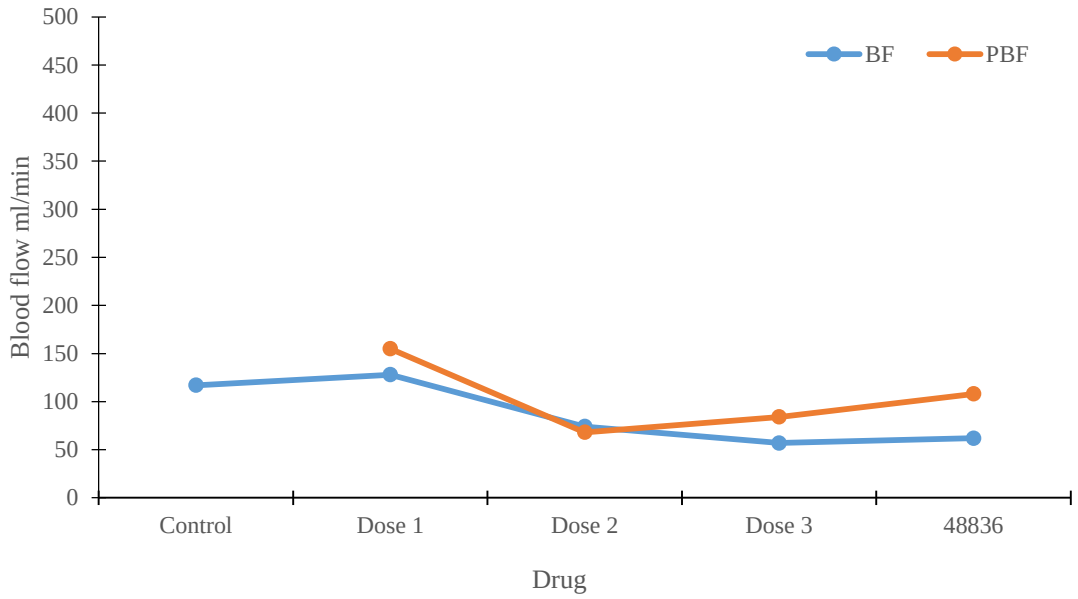

Figure A32. Blood flow measurements from gilt 39-1 on drug treatment 8165.

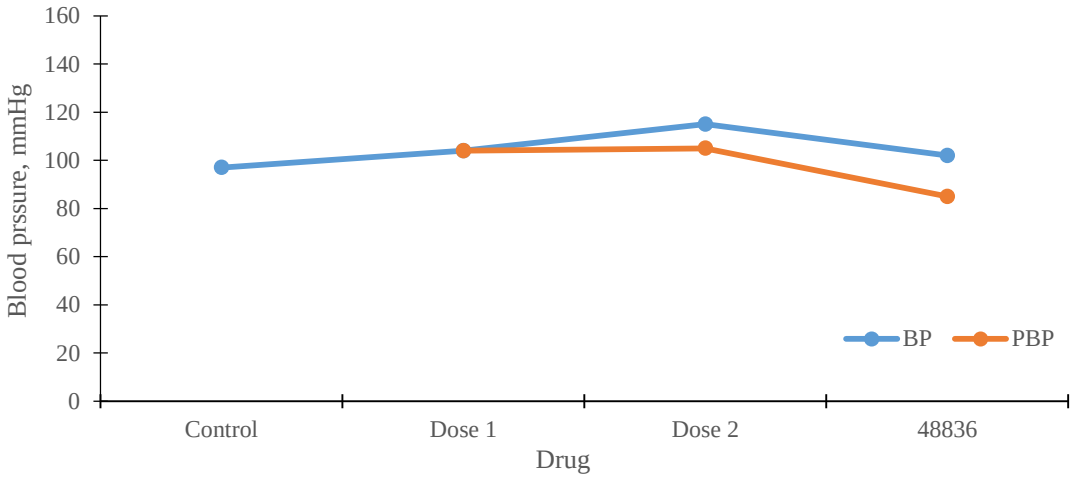

Figure A33. Blood pressure measurements from gilt 34-5 on drug treatment 51624.

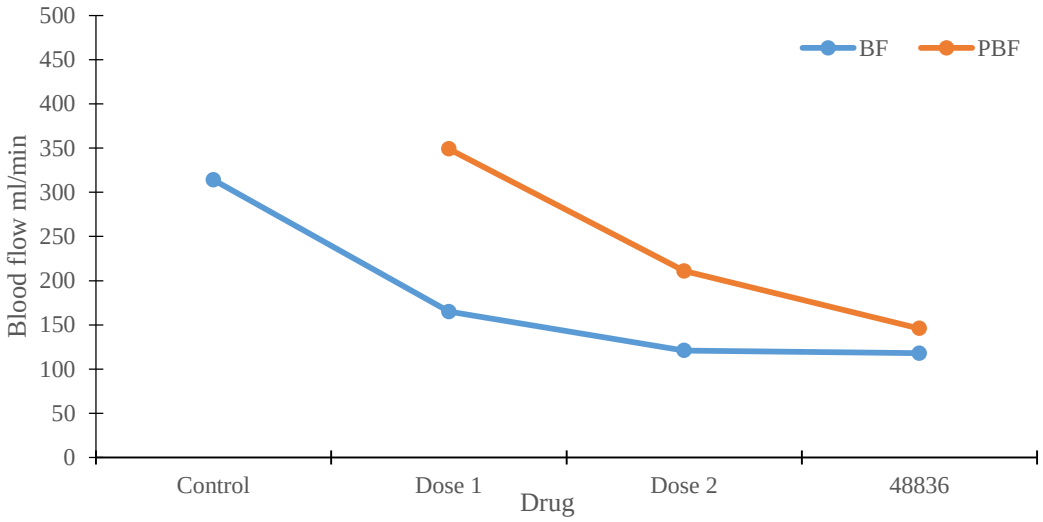

Figure A34. Blood flow measurements from gilt 34-5 on drug treatment 51624.

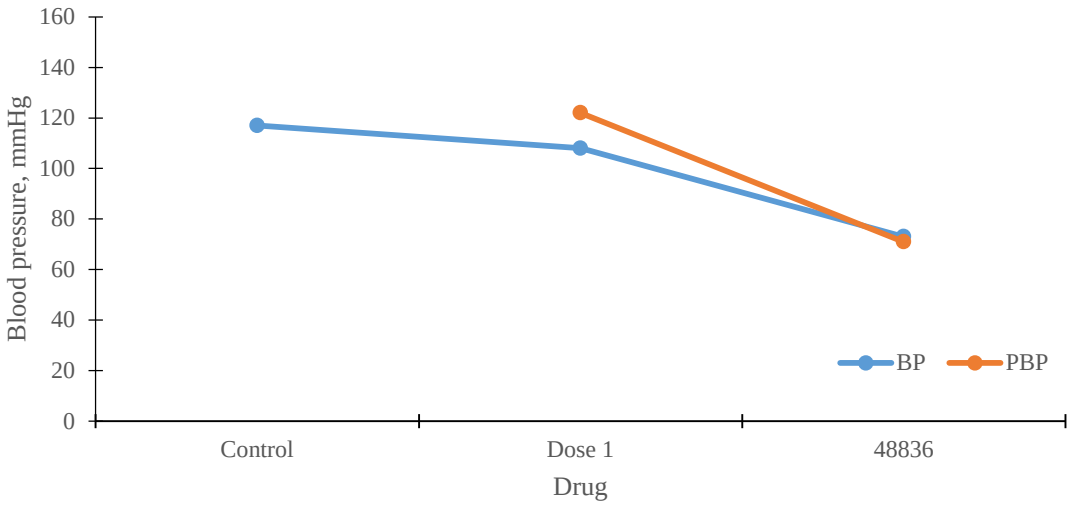

Figure A35. Blood pressure measurements from gilt 31-5 on drug treatment 51624.

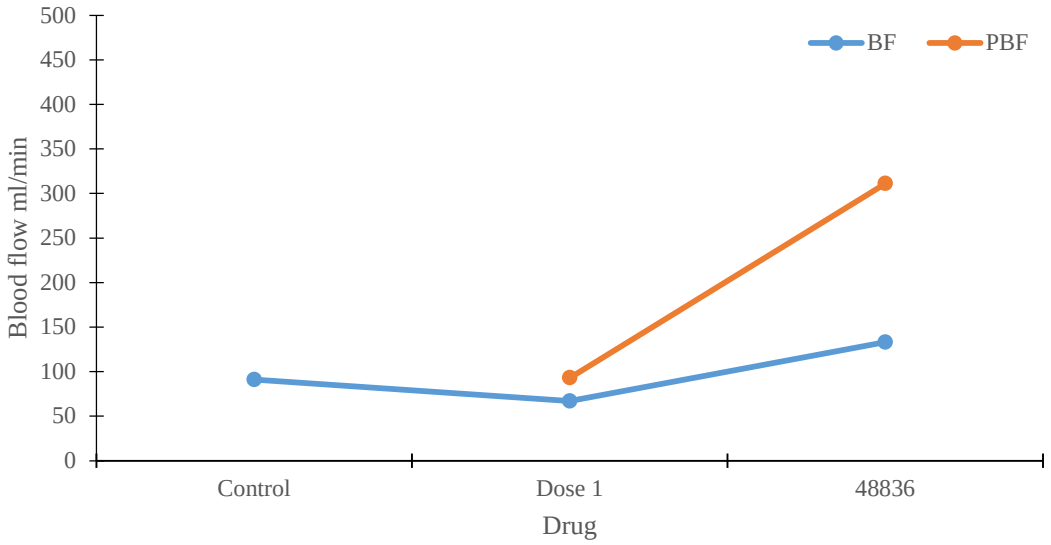

Figure A36. Blood flow measurements from gilt 31-5 on drug treatment 51624.

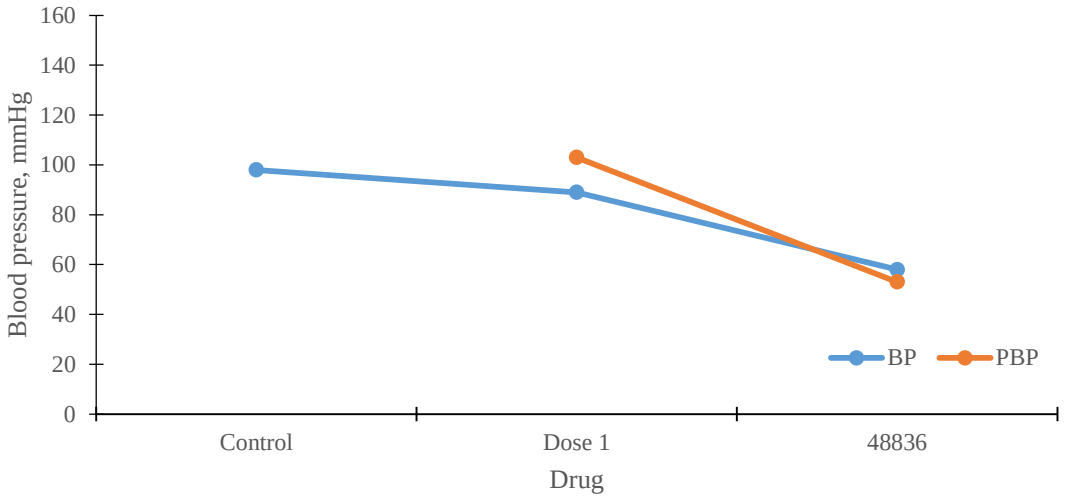

Figure A37. Blood pressure measurements from gilt 31-3 on drug treatment 51624.

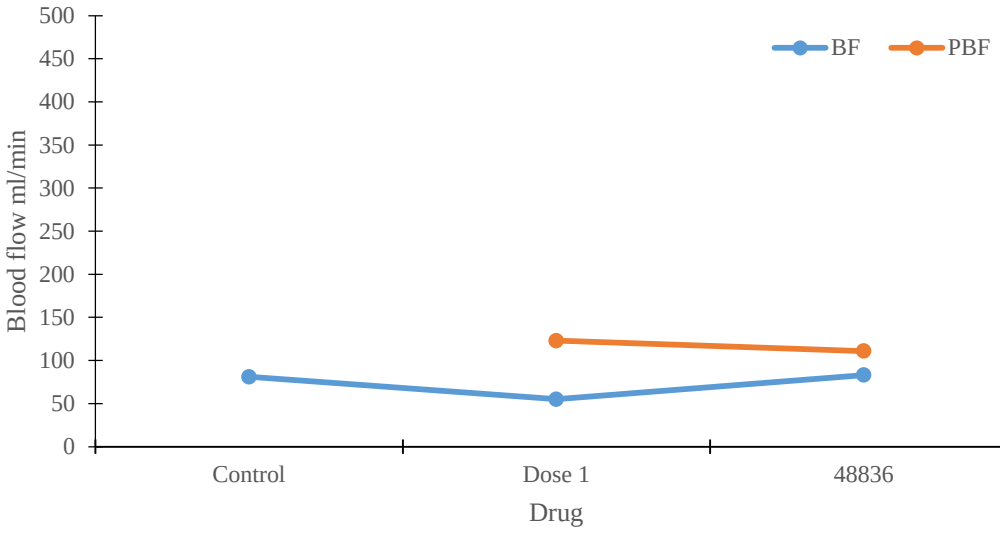

Figure A38. Blood flow measurements from gilt 31-3 on drug treatment 51624.

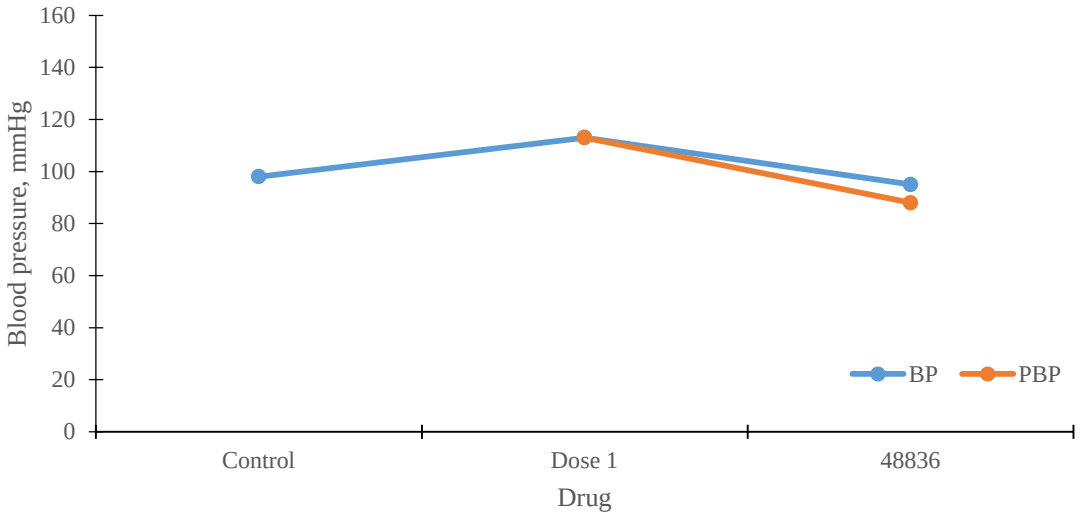

Figure A39. Blood pressure measurements from gilt 28-29 on drug treatment 51624.

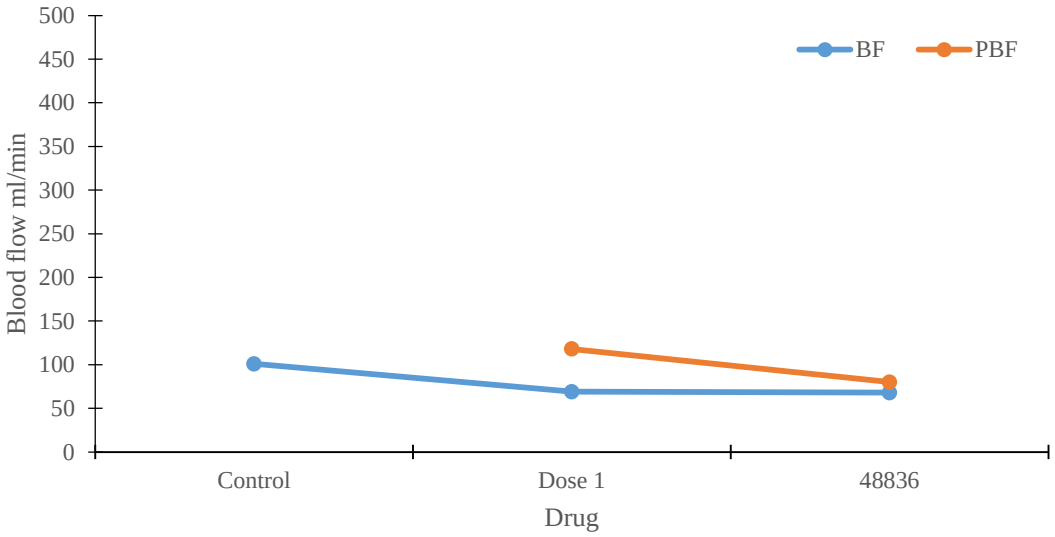

Figure A40. Blood flow measurements from gilt 28-29 on drug treatment 51624.