REWARMING HYPOTHERMIC PIGLETS WITH 915 MHz MICROWAVE RADIATION

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ABSTRACT

Chilling, leading to hypothermia, is one of the major causes of death of neonatal piglets. Microwave radiation (MWR), with its ability to penetrate tissue, can provide an efficient means of generating heat within the body. A first trial determined a safe and efficient rate of rewarming using a 915 MHz microwave (MW) unit. Hypothermia was induced in 46 neonatal piglets weighing less than 1.25 kg each. Prior to suckling the piglets were dried, weighed, sexed, and their rectal temperatures were recorded. Their rectal temperatures were reduced to 25°C by placing the piglets in a 10°C cooling unit following a protocol approved by the University Animal Care Committee. Piglets were randomly assigned to be rewarmed at the rate of 0.5, 0.75, or 1.0 °C min^{-1} using 915 MHz MWR. After being rewarmed to 38°C, the piglets were returned to the sow and allowed to suckle. The rectal temperature of each piglet was recorded every 10 minutes until a stable temperature of 38°C was attained in order to determine the temperature drop subsequent to rewarming and recovery time. Body weights of the piglets were recorded weekly for 28 days. Visual examination revealed no gross abnormalities in piglets rewarmed at any intensity. Initial birth weight and treatment rewarming rate had no significant ($P>0.05$) influence on the growth rate during the 28 day study period. There was no significant difference ($P>0.05$) in the recovery times, in which piglets attained 38 ° C after rewarming, between treatment groups. It was concluded that the rewarming rate of 1.0°C min^{-1} was the most time efficient and provided a safe and effective treatment for hypothermic piglets. A second trial compared rewarming of hypothermic piglets with MWR vs. infrared radiation (IRR). The cooling and "after rewarming" protocol was the same as in the first trial. Thirty nine piglets were randomly assigned to be rewarmed by MWR or IRR. The MW unit was programmed to rewarm at a rate of approximately 1 °C min^{-1}, while the infrared (IR) heating was provided by a 250 W IR heating lamp placed 30 cm above the piglets. Rewarming time was shorter ($P<0.05$) in MW than in IR rewarmed piglets (19.70 ± 6.32 vs 118.91 ± 5.00 min), respectively. Treatment did not influence growth rate during the study period ($P>0.05$). It was concluded that 915 MHz MW rewarming is a safe and more efficient method for rewarming hypothermic piglets than using the conventional IR lamp. The third trial was performed to evaluate the short-term biological effects following the established rewarming procedures. Blood samples were taken from 16 experimental piglets at birth, after cooling, after rewarming, and at sacrifice. The piglets were sacrificed 48 hours after rewarming and dissected for subsequent plasma and tissue analysis. Rewarming time was shorter ($P<0.05$) for MW than IR rewarmed piglets. Neither plasma cortisol or glucose levels showed significant differences ($P>0.05$) between treatments at any of the four sampling times. However, differences were significant ($P<0.05$) within treatments between times. Rewarming treatment did not influence liver glucose or glycogen levels. The percentage area of the adrenal gland zones showed no significant difference ($P>0.05$) between treatment groups. It was concluded that rewarming hypothermic piglets with 915 MHz MWR does not appear to cause any detrimental effects to these variables assessed. Thus it may provide a safe and efficient method for treating piglet hypothermia in a commercial farm situation.

Key Words: piglet, hypothermia, microwaves, infrared, rewarming

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GLOSSARY OF ABBREVIATIONS

ACTH:	adrenocorticotropic hormone
ANOVA:	analysis of variance
CO_2:	carbon dioxide
cm:	centimeter(s)
CNS:	central nervous system
CRF:	corticotropin releasing factor
CW:	continuous wave
d:	day(s)
dL:	deciliter
° C:	degrees Celsius
eV:	electron volt
FP:	forward power
g:	gram(s)
GIF:	growth inhibitory factor
GH:	growth hormone
GHz:	Gigahertz
Hz:	hertz
h:	hour(s)
HHA:	hypothalamic hypophysial axis
ISM:	industrial, scientific, medical
IR:	infrared
IRR:	infrared radiation
kg:	kilogram(s)
KHz:	kilohertz
L:	liter(s)
MHz:	Megahertz
m:	meter(s)
mg:	milligram(s)
mL:	milliliter(s)
min:	minute(s)
mm:	millimeter(s)

MRI:	magnetic resonance imaging
MRS:	magnetic resonance spectometry
μW:	microwatt(s)
MW:	microwave
MWR:	microwave radiation
mW:	milliwatt(s)
NES:	neuroendocrine system
%	percent
pW:	picowatt(s)
P:	probability
RIA:	radioimmunoassay
RF:	radio frequency
RFR:	radio frequency radiation
RP:	reflected power
rpm:	revolutions per minute
SAR:	specific absorption rate
SD:	standard deviation
SEM:	standard error of the mean
SAS:	statistical analysis software
temp:	temperature
TRH:	thyroid releasing hormone
TSH:	thyroid stimulating hormone
W:	watt(s)

INTRODUCTION

Piglet mortality continues to be a major problem in the swine industry. Even today, with intensive farming practices such as the use of farrowing crates (Phillips and Fraser 1993), and improved knowledge of piglets' thermal requirements, pre-weaning mortality rates remain between 15-30 % (Bereskin et al.1973; Straw 1984). The pig mortality rate for 1992 in PEI was 25.2 % (Statistics Canada 1992), probably reflecting large pre-weaning losses.

Susceptibility to cold and subsequent hypothermia are major factors causing neonatal piglet mortality (English and Morrison 1984). Hypothermia also predisposes the piglet to starvation, crushing, and scours (Mount 1968; McGinnis et al. 1981). Traditional methods for treating piglet hypothermia such as the infrared heat lamp and warm water immersion are often unsuccessful and time consuming, hence the need for an alternative treatment.

When microwave or radiowave energy impinges on a biological tissue it causes oscillation of polar molecules increasing the kinetic energy of these molecules, with the consequent generation of heat (Repacholi 1981). Radiowave radiation has been successfully used to rewarm severely hypothermic animals (Gordon 1982; Olsen and David 1984). Due to its similar characteristics, microwave radiation (MWR) could also be beneficial in treating piglet hypothermia, thus decreasing piglet mortality.

The objectives of this study were to: 1) establish a safe and efficient rewarming rate using 915 MHz MWR to rewarm hypothermic piglets, 2) to compare the effectiveness of MWR rewarming to the traditional infrared (IR) heat lamp, and 3) to compare the short term physiological effects of the two rewarming methods.

LITERATURE REVIEW

Piglet Mortality

Pre-weaning mortality is a major problem in the swine industry. Mortality rates of 15-30 % make it very difficult for the producer to improve sow productivity (Straw 1984). Such high losses place a major economic burden upon the swine producer who has already invested substantial capital in feed, labour, and infrastructure to produce the piglets which do not survive.

The first week of the piglet's life is the most critical period for its survival. On day one, 32 % of pre-weaning deaths occur, while on days two and three the rates of mortality are 20 % and 16 %, respectively (Kerncamp 1965; Foley et al. 1971).

Chilling, leading to hypothermia, is the second highest cause of death after crushing (Curtis 1983; English and Morrison 1984). Hypothermia makes the piglet susceptible to starvation, crushing, and disease (Mount 1968; McGinnis et al. 1981). Immediately after birth the piglet is exposed to a fluctuating, normally cool, environmental temperature and must begin to thermoregulate (Curtis 1970). The smaller newborn piglet has such a large surface area relative to its heat capacity that a small change in heat loss is reflected in a large change in body temperature (Curtis 1970).

The rectal temperature of the piglet drops 2°C during the first hour after birth and then gradually returns to normal during the next 24-48 hours (Curtis 1983). Since the newborn piglets use body heat to evaporate the amniotic fluids, the smaller piglets experience a greater drop in temperature than the heavier ones soon after birth

(Mount 1968). This is because the body surface area of the piglet is directly proportional to the rate of heat loss; thus a smaller piglet which has a greater surface area to body weight ratio, loses heat faster than the heavier piglet.

In an attempt to conserve body heat, the newborn piglet uses physiological processes such as peripheral vasoconstriction and piloerection. The sparse hair coat of the piglet at birth and its low body fat content, which is only 1 % at this time, result in an extremely low ability to prevent heat losses (Mount 1968).

The ability of the piglets to resist cold stress is very limited immediately after birth, but as time goes by they are better able to cope with it. Curtis (1983) exposed 6, 18, and 20 h old piglets of similar weight to 4°C air for 90 min and found that their rectal temperature decreased by 4.4, 3.2, and 0.9°C, respectively.

Another factor which contributes to piglet losses is the depletion of energy reserves before nursing. This results in hypoglycemia. Glycogen, an important energy reserve for neonates, is stored in the liver and skeletal muscles (Mount 1968). Fat stores are also a very important energy reserve; however, the newborn piglet has very little reserve fat. Fasting may cause a drastic drop in blood glucose levels in the piglet from 100 mg dL^{-1} to 10 mg dL^{-1} (Mount 1968). Hypoglycemia in the piglet can result in lethargy, coma, and death within 24 h if the condition is left untreated (Mount 1968; McGinnis et al. 1981).

Introduction to Microwave Properties

Microwave radiation consists of electric and magnetic fields that vary in space with time and are propagated through free space at the speed of light, approximately 2.998×10^8 m s^{-1}. Electromagnetic energy consists of waves of electric and magnetic forces that carry energy as they propagate.

Important characteristics of electromagnetic energy are wavelength and frequency. These characteristics and the manner of their physical behavior are functions of the rate at which the electric and magnetic fields vary. These variations are periodical and sinusoidal, thus the frequency can be defined in terms of cycles or complete alterations per second. The equation for calculating frequency is $f = c/\lambda$; where f is the frequency of oscillations or cycles per second expressed in Hertz (Hz), c is the distance a light wave moves in one second (3×10^8m s^{-1}), and λ is the wavelength expressed in meters. Wavelength is a measure of the distance a wave travels during one cycle. Energy normally considered to be in the microwave range involves wavelengths of approximately 30 cm to a fraction of a centimeter with frequencies in the range of 300 MHz to 300 GHz (Johnson and Guy 1972).

The electromagnetic spectrum consists of ionizing and non-ionizing energy. Microwaves having relatively low frequency are classified as non-ionizing radiation. As its name suggests, non-ionizing radiation does not have enough energy to remove an electron from its orbit. The minimum photon energy required for ionization is 12 eV (World Health Organization 1981). The photon energies of microwaves range from 1.25×10^{-6} and 1.24×10^{-3} eV, values which are well below the minimum energy required for ionization. Ionizing radiation can break chemical bonds causing molecular changes and tissue damage.

The quantities and units for describing non-ionizing microwave energy have been described extensively by Michaelson and Lin (1987). Power density is an expression of the exposure in terms of incident power per unit area, with some common units of W m^{-2}, mW cm^{-2}, μW cm^{-2}, or pW cm^{-2} (Michaelson and Lin 1987).

The amount of energy absorbed from electromagnetic radiation per unit mass is the specific absorption rate (SAR), which is expressed in W kg^{-1} or mW g^{-1}. Specific absorption rate distribution indicates the SAR pattern inside the body. Factors that affect SAR distribution within a mass include incident radiation, body geometry and orientation, and the dielectric property of the absorber (Durney et al. 1980).

Hot spots are areas where there is a significant rise in temperature with respect to the adjacent areas. This happens when the MWR propagating in one medium impinges on a second medium having different electromagnetic properties. The reflection of the incident radiation is great and combines with the incident wave to form a standing wave. It is this standing wave combination of the transmitted and reflected radiation that may generate a large rise in temperature in such an area (Michaelson and Lin 1987).

Types of MW and RF Irradiation Systems

There are many types of systems used to irradiate biological matter. Michaelson and Lin (1987) provide a detailed discussion on these systems. Following are brief descriptions of some of the most common applicators.

Anechoic cavity. This is an enclosed shielded cavity that is designed to minimize reflected energy as its walls and ceiling are lined with material of highly absorbent properties. Anechoic chambers, with their ability to provide a large field uniformity, allow specimens with large size variations to be irradiated.

Some disadvantages of using the anechoic chamber include the high cost of building and operating the system, as well as the often uneven heating pattern that may occur within the chamber (Durney et al. 1980).

Multimode cavity. The multimode cavity is a small shielded enclosure, usually a rectangular box constructed of metal. The domestic microwave oven found in many households is an example of such a cavity. The multimode cavity distributes power in as many modes or patterns as possible in order to provide a uniform field. Mode stirrers consisting of metal fan blades, are used to increase the number of resonant modes and to change the cavity mode structure (Michaelson and Lin 1987).

Modified microwave ovens are commonly used in biological research on small animals, and on isolated tissue specimens (Justesen et al. 1971). Multimode cavities have the advantage of being quite portable, and their initial cost of production is relatively low. Within these cavities however, hot spots occur which may unevenly distribute heat within a specimen.

Waveguides. Waveguides are usually rectangular or circular metal enclosures with their exact dimensions determined by the frequency (Durney et al. 1980). Hollow waveguide systems can achieve a substantial exposure level with considerably less source power than other exposure devices. Energy is in the form of a travelling wave going through the waveguide, usually in one direction. Waveguide fields may be calculated, and in some cases are sufficiently uniform to justify waveguides as a method of choice for irradiating small animals within an enclosure.

An advantage in using a waveguide system is that the energy absorbed by the specimen is normally large in comparison to the energy lost to the walls. Uniformity of irradiation can be easily influenced by the size, shape, and location of the specimen within the waveguide.

Partial body irradiation applicators. Antennas are used to deliver energy to specific part of the specimen. Antennas may be used as non-contact or direct contact applicators. Non-contact antennas deliver energy without touching the subject, and often result in the undesirable scattering of electromagnetic energy, causing unnecessary exposure to the subject as well as the experimenter (Michaelson and Lin 1987).

The more desirable, direct contact antennas deliver localized energy to the appropriate area of the subject by operating in contact with the surface of the body. These applicators usually operate at either 915 or 2450 MHz frequency. A relatively uniform power absorption and the production of a high temperature rise within tissues may be attained with these applicators (Johnson and Guy 1972).

Direct contact applicators are very useful in diagnostic and therapeutic medicine The main disadvantage of such applicators is that the subject may have to be sedated or immobilized.

Induction coils. Helical coil systems consist of a copper coil wound around a plastic pipe having an inner plastic pipe to keep the subject from direct contact with the induction coil. The coil is able to provide a uniform heating pattern, but this system lacks the compactness and ease of shielding that other surface applicators provide. Helical induction coils have been used successfully in rewarming hypothermic monkeys (Olsen and David 1984).

Factors that affect MW and RF absorbtion

The literature regarding MWR and radio frequency radiation (RFR) of animals contains many inconsistencies and many results are not comparable with each other. The difficulties in comparing the results of most studies are due to the differences in the MWR application, the methods of measuring MWR absorption, the frequency and duration of exposure, as well as the species of animals used and their initial body temperatures (Michaelson and Lin 1987)(Table 1).

Table 1. Factors that affect microwave and radiofrequency absorption (from Michaelson and Lin 1987).

Physical parameters of the electromagnetic source	Biological parameters	Artifacts
Frequency	Tissue dielectric properties	Ground or conductor plate
Polarization	Size, geometry	Container
Modulation	Relation to polarizations	Metal implants
Power Density	Spatial relations of animals	Shielding materials
Field Pattern		Metal or nonmetallic objects in the field
Measuring technique		
Calibration technique		
Power		
Transmitting and Radiating equipment		
Chamber materials and dimensions		

Biological Responses of Animals Exposed to Radiowaves or Microwaves

Behavior. Behavior studies may be classified into two categories. There are innate behaviors, such as eating and locomotor activity, and acquired behaviors, which are learned responses such as those involving operant conditioning (Blackwell and Saunders 1986). The studies discussed here primarily involve acquired behavior responses. Comparisons between effects of microwaves on the behavior of animals are difficult due to the variability in the type of exposure and dosimetric techniques; therefore it is very difficult to relate experimental results in non-identical studies.

Rats and monkeys were exposed for 60 min to 2450 MHz continuous wave (CW) MWR at various power densities to determine at what level a behavior disruption in operating a food dispenser occurred (de Lorge 1978). The threshold of disruption occurred at the power densities of 28 mW cm^{-2} in rats, 45 mW cm^{-2} in squirrel monkeys, and 67 mW cm^{-2} in rhesus monkeys. Disruption in behavior may have been caused more by the increase in heat load, reflected in a rectal temperature increase of 1°C, than any direct action of MWR on the central nervous system (CNS).

Rats exposed to either pulsed or CW radiation with frequencies of 2860 MHz and 9600 MHz for 30 min showed a decreased ability to manipulate food dispensers, as power density increased from 5 to 20 mW cm^{-2}, in a multiple reinforcement schedule (Thomas et al. 1975) Although it appeared that the CNS was affected by the MWR such effects were also observed when the animal interacted with its environment. Therefore, the degree of disruption in the animal's behavior was very minimal and could not be clearly attributed to the electromagnetic effect of microwave exposure.

No detrimental behavioral or health effects were detected when 8-day- old broiler chicks used microwaves as a heat source and chose the total exposure time in an operant control experiment. The chicks were exposed to 2450 MHz at a power density of 26 mW cm^{-2}, 13 mW cm^{-2}, or 10 mW cm^{-2} (Morrison et al. 1985).

Since thermal stress may be the cause of disruption of operant behavior, it is necessary to investigate whether thermoregulatory behavior is affected at lower SARs. Stern et al.(1979) placed shaved rats in a 3.9 - 5.3°C cold chamber. The rats responded by obtaining IRR as a positive reinforcer. When the rats were exposed to 2450 MHz microwaves at power densities of 5, 10, or 20 W cm^{-2}, their rate of IRR usage was reduced, suggesting that the MW energy substituted for some of the heat obtained from the IR lamp.

Microwave dose-response relationships on behavioral tasks in monkeys were evaluated by exposing the heads of monkeys to 2450 MHz CW energy via an antenna for 2 min intervals, up to a total of 40 min per day (Galloway 1975). No behavioral effects were observed when MW power was less than 15 W but at power levels greater than 25 W, severe burns, and in some cases, convulsions occurred. However, the performance of operating a food dispenser was not consistently changed in those animals not affected by convulsions. The initial hypothesis of this research was that the amount of energy absorbed by the head could be related to behavioral effects shown; yet the above mentioned results proved this basic assumption incorrect (Galloway 1975).

It has been determined that for the Rhesus monkey, colonic temperature rise is a better predictor of behavior disruption than either power density or estimates of whole-body-average rates of energy absorption (de Lorge 1984).

There is presently no standard, convenient method for direct measurement of power absorption in live tissue; therefore results of various researchers are difficult to compare.

Neuroendocrine. The hypothalamus is a sensitive part of the endocrine system where small electrical or chemical stimuli from higher brain centers and peripheral nerves may produce significant alterations in hormone secretion by the hypophysis (Michaelson 1976).

There are two views on the effects of MWR on the endocrine system. Some researchers believe that the neuroendocrine system (NES) response to MWR is due to thermal stimulation of the hypothalamic-hypophyseal system or the particular endocrine gland affected. Other researchers support the theory that any response to MWR or radio frequency radiation (RFR) is due to the direct interaction of MWR with the CNS (Michaelson 1976). Regardless of the views taken, NES alterations may not necessarily be pathologically significant because the function of the NES is to maintain homeostasis; thus hormone levels fluctuate to maintain this stability.

Thyroid. The function of the thyroid within the NES is dependent upon and responsive to any functional disturbances in the other members of the system (Lu et al. 1985). Thyroid hormones act at the cellular level regulating processes to maintain homeostasis by changing metabolic rate (Lu et al. 1985). The thyroid gland is essential in the regulation of basal metabolism. It is the key component in the metabolic generation of heat within the tissues (Lu et al. 1985). Thyroid stimulating hormone (TSH), produced in the pituitary gland, is stimulated by thyroid releasing hormone (TRH) from the hypothalamus or inhibited by thyroid hormones, thyroxine and triiodothyronine. Michaelson (1976) found that rats, exposed to 2450 MHz CW (1mW cm^{-2}), or 10 mW cm^{-2} for 8 h d^{-1} for 8 wk, had no alteration in thyroid structure or function. Thyroid hormone levels of rats exposed to 2450 MHz MWR decreased as the power density increased from 5 to 25 mW cm^{-2} (Vetter 1975). There appear to be two ways in which microwave energy affects thyroid function. The first being the local thyroid stimulation or inhibition caused by high intensity MWR (Lu et al. 1980), and the second is being axial inhibition involving the homeostatic reaction of the hypothalamus and hypophysis to the increased heat load. The increased heat load demands an appropriate response to a specific stressor and in turn lowers the level of metabolism (Lu et al. 1980).

Rats exposed to 2450 MHz MWR for 1 h at 40 to 70 mW cm^{-2} showed increased serum thyroxine levels while rats exposed to 20 mW cm^{-2} for 4 to 8 h had a decrease in serum thyroxine levels (Lu et al. 1985). Changes in serum thyroxine levels should not be used as an accurate indication of response to MWR due to sensitivity to extraneous factors (Lu et al. 1987).

Adrenal. There were no changes in adrenal weight, plasma epinephrine, or plasma corticosterone levels when rats were exposed for 4 h to 2450 MHz CW at 10 mW cm^{-2} (Lu et al. 1977).

A significant positive relationship between mean colonic temperature and plasma corticosterone levels was shown in rats exposed to 2450 MHz CW energy for 30-60 min at a power density of 0-60 mW cm^{-2} (Lotz and Michaelson 1978). Corticosterone levels increased during microwave exposure and then dropped sharply after radiation ceased, thus showing a transient adrenocortical response.

Adrenocortical stimulation is accepted to be the result of exposure to a stressor (Selye 1946). The evidence shows that exposing rats to more than 25 mW cm^{-2} MWR stimulates the hypothalamic hypophyseal adrenal (HHA) axis through the central nervous system (Lu et al. 1980). Studies using less than 25 mW cm^{-2} produce no conclusive results (Lu et al. 1977).

Growth hormone (GH). Growth hormone is secreted by the adenohypophysial somatotropic cells after stimulation by growth hormone releasing hormone (GRH) (Michaelson 1980).

Michaelson (1976) found that rats exposed to 2450 MHz CW for over 60 min at 13 mW cm^{-2} had an increase in GH levels, whereas those rats exposed at 36 mW cm^{-2} showed a decrease in GH levels. Stressors placed upon rats are known to cause a decrease in plasma GH levels (Lu et al. 1987). The MWR exposure at 36 mW cm^{-2} may have created a stressor high enough to decrease the amount of GH released. The threshold for GH inhibition in rats exposed to 2450 MHz CW for 30 to 60 minutes was 50 mW cm^{-2} (Michaelson 1976). An increase in somatostatin could have acted as an inhibitor of TSH and TRH (Michaelson and Lin 1987).

In conclusion, the acute effects of RF/MWR on the hypothalamic hypophyseal function are generally an increase in adrenocorticotropic secretion and a decrease in thyrotropin and growth hormone secretion.

Exposure to MWR at a level high enough to cause an interference with the body's ability to maintain homeostasis causes corticotrophin releasing factor (CRF) to stimulate the release of adrenocorticotropic hormone (ACTH) from the anterior pituitary. The release of ACTH then stimulates the secretion of glucocorticoids from the adrenal cortex (Lu et al 1986).

Growth and reproduction. There are reports that suggest that certain treatments with microwaves produce deleterious effects on embryo and postnatal growth. Forty-eight-hour old chick embryos exposed to 2450 MHz CW MWR for 280 to 300 min at power levels of 20 to 40 mW cm^{-2} showed an increase in yolk temperature from 37°C to 42.5°C, and the development of the hind limb, tail, and allantois was suppressed (Van Ummersen 1961).

An increase in neonatal deaths was seen when squirrel monkeys in utero weighing 4.2 kg were exposed to 2450 MHz MWR to study the postnatal effects (Kaplan 1981). It has been reported that in many cases these effects can be attributed to excessive elevation in temperature (Michaelson and Lin 1987).

Mouse spermatozoa exposed to 2450 MHz CW radiation for 1 h at SARs greater than 25 W kg^{-1} showed a significant decrease in *in vitro* fertilization of mouse ova (Cleary et al. 1989). This effect was not associated with detectable heating, morphological alterations, or the killing of sperm.

The effect of MWR on the testes has been studied rather extensively (Ely et al. 1964; Imag et al. 1948). The sensitivity of sperm cells to temperature changes is well known (Chowdhury and Steinburger 1970). It has been indicated that the testes may be affected when exposed to high power densities, but most of these responses can be related to the heating of the organs (Michaelson and Lin 1987).

Berman et al. (1982) exposed male rats to 2450 MHz MWR to study any mutagenic or reproductive affects. The rats were exposed to 4 or 5 h of radiation per day from day 6 of gestation to the 90^{th} day of age at 5 mW cm^{-2}, or beginning on the 90^{th} day of age at 10 or 28 mW cm^{-2}, respectively. Following treatment the rats were bred to pairs of untreated females. Microwave exposed males showed no significant evidence of germ cell mutagenesis compared to the sham exposed males. Lower pregnancy rates were seen in response to the highest power density of 28 mW cm^{-2}, which caused temporary sterility.

Broiler and laying birds were exposed to 600 MHz CW radiation at power densities of 0.02 and 400 pW cm^{-2} from hatching up to 476 days of age without effect on growth rate, feed efficiency, egg production and quality, hatchability, and mortality (Kondra et al. 1972).

Cardiovascular. Many researchers have reported that microwave exposure may result in direct or indirect effects on the cardiovascular system. Rats exposed to 2450 MHz MWR at a power density of 6.5 mW g^{-1} for 30 min had an initial increase in temperature which subsequently declined 3 h post radiation (Phillips et al. 1975). A decrease in metabolic rate as well as a mild bradycardia, and irregular heart rate occurred. Rats exposed to 68.2 cal min^{-1} for 30 min exhibited severe bradycardia and irregular heart rates. An incomplete heart block also occurred in these rats (Phillips et al. 1975).

Isolated chick embryo hearts exposed to 2450 MHz MWR at a power density of 3 mW cm^{-2} responded to CW microwaves with a slight bradycardia, while exposure using a pulse modulated field at the same power density caused an increase and normalization of the heart rate (Caddemi et al. 1986). These effects were not believed to be related to an increase in tissue temperature. Exposure of isolated rat hearts to 960 MHz CW MWR that caused no rise in tissue temperature resulted in increased bradycardia. Tachycardia occurred when the power density was high enough to cause an increase in tissue temperature (Reed et al. 1977).

Immunological/Hematological. The interactions of RF/MWR with the hematological and immunological system are complex and difficult to define. It is particularly difficult to determine the amount of energy absorbed by the live subject. Although it is possible to measure the average energy absorbed, it is difficult to determine the amount of energy absorbed at specific sites within the animal, thus the possibility of the occurrence of undetected hot spots.

Hot spots may occur anywhere in the body and may affect critical areas, such as those abundant in immune or hematopoietic cells or types of cells whose altered physiology may affect immunological and hematological homeostasis (Roberts 1981).

The offspring of pregnant mice exposed to 2450 MHz MWR at a power density of 28 mW cm^{-2}, with a SAR of 16.5 mW g^{-1}, for 100 min d^{-1} from days 6 to 18 of gestation showed no difference on the development of titers to sheep red blood cells, mitogen-stimulated lymphocyte proliferation and natural killer cell activity at 3 and 6 wk of age (Smialowiecz et al. 1982).

Broiler chicks were trained to obtain supplementary heat from either a 250 W IR bulb or a device which supplied 2450 CW MWR with a power density of 13 mW cm^{-2}, for supplementary heat (Braithwaite et al. 1985). In the 4 wk monitored, operant exposure to MWR did not result in short term stress as measured by corticosterone levels, nor in any immunological disruptions measured by histological examination of the spleen, bursa, adrenal, and thyroid. The analysis of heterophil-lymphocyte ratios, packed cell volume, and total plasma protein levels suggested no effect on the immune system (Braithwaite et al. 1985).

It has not yet been determined if effects of MWR on the hematological and immunological tissues are mediated independent of thermal effects. If the thermal effects are not in excess of the subject's physiological regulatory system, they may be beneficial rather than detrimental (Roberts 1981).

Ocular. There has been much concern regarding the effects that MWR may have on the eye, primarily the lens. The lens is an avascular structure, thus making it less effective in dissipating heat than the other organs and tissues in the body. Most of the research on the effects of MWR on the eye have been conducted on the New Zealand white rabbit (World Health Organization 1981). The occurrence of microwave cataracts have been related to the localized temperature rise in the crystalline lens, which when overheated undergoes protein denaturation.

Intraocular temperatures of 45 to 55°C have been measured, and determined to be the range in which cataractogenesis may occur (Guy et al. 1975). The threshold for cataractogenesis has been determined to be 150 mW cm^{-2} for a 60-100 min exposure time using frequencies of 200 MHz to 10,000 MHz (Michaelson and Lin 1987).

Exposure levels that are high enough to cause cataracts also cause other ocular reactions. Swelling and chemosis of bulbar and palpebral conjunctivae, pupillary constriction, hyperemia of the iris and limbal vessels, vitreous floaters and filaments occur (Michaelson and Lin 1987). Rabbits exposed to 35 and 107 GHz for 15 min to 1 h at power densities of 5 to 60 mW cm^{-2} had keratitis, inflammation of the cornea, and corneal damage (Rosenthal et al. 1976). Under conditions of controlled hypothermia, no damage to the eye occurred even under exposure to MWR or RFR at levels that were cataractogenic (Kramer et al. 1975).

Most of the threshold values for ocular damage are based on acute near- field exposure. No cataracts have been reported in animals exposed to far-field, whole body, MWR even at semi-lethal intensities (Michaelson and Lin 1987).

Medical Use of Electromagnetic Fields

There are many diverse uses of time varying magnetic fields in the area of medicine today. Diagnostic applications include magnetic stimulation and magnetic resonance imaging (MRI) (Barker et al. 1985), spectroscopy (MRS) (Budinger and Lauterbur 1984), and conductivity (impedance) measurements (Fiorotto et al. 1987).

Therapeutic applications of electromagnetic energy at frequencies of 1 Hz to 300 Hz have been well demonstrated for bone and tissue growth and repair (Leaper et al. 1985; Madronero et al. 1988). Hyperthermia and selective tissue destruction using electromagnetic energy operating in the KHz and GHz range is used in cardiac angioplasty and ablation, aneurysm treatment, and tumor resections (Stuchly 1990).

Localized hyperthermia, which has been used extensively in the last decade, is becoming a recognized form of cancer therapy. Its use has increased especially as a compliment to other modalities such as radiotherapy and chemotherapy (Storm et al. 1985; Stuchly 1990). Treating cancer with localized hyperthermia requires delivering sufficient energy to the designated tissue to increase its temperature to approximately

44°C. Frequencies commonly used for this range from 200 MHz to 300 GHz (Hand 1987). Many of the devices operate at frequencies allocated for industrial, scientific, and medical (ISM) applications to avoid any interferences with other electronic systems such as those used in communications (Stuchly 1990).

The type of applicator used depends on whether the tumor is superficial or deeply located and whether localized or regional hyperthermia is required (Mittal et al. 1990).

One of the major problems in clinical hyperthermia is the difficulty in providing an adequate and homogenous heating (Ryan 1990). Commercially available applicators operating at 915 MHz have only the ability to adequately heat tissue up to a maximum depth of 3 cm. Mittal et al. (1990) demonstrated that by implanting additional layers of interstitial microwave antennas at required depths greater than 3 cm, and by simultaneously exciting these applicators as well as an external applicator, it is possible to extend the depth of heating. This simultaneous use of localized external and interstitial microwave hyperthermia may be especially useful for heating superficial tumors more homogenously in areas of poor coupling, and/or curved surfaces where the 915 MHz applicator may not be adequate (Mittal et al. 1990).

DuBois et al. (1990) concluded from their studies that superficial hyperthermia, induced by 2450 MHz MWR, was a very useful treatment of chest wall recurrences in breast cancer, for which the therapeutic possibilities have been limited until now.

The applications of present hyperthermia generating devices are often inadequate in achieving the desired temperature distribution in most tumors. The adequacy of this treatment may depend on the development of appropriate applicators capable of such desired heating. Gottlieb et al. (1990) showed that submillimeter diameter microwave interstitial hyperthermia applicators operating at 915 MHz provided adequate heating to designated tissues. The use of these applicators caused less local tissue trauma than the larger diameter devices. The small diameter applicators may be extremely useful in the percutaneous treatment of deep seated tumors and in intraoperative treatments. Intraluminar or intravascular access to tumors has also been successfully performed with these applicators (Gottlieb et al. 1990).

Animal Rewarming Studies

Microwave energy, with its ability to penetrate several centimeters into tissue, has been used in cases where a rapid rate of rewarming is required without increasing the temperature to a lethal level (Gordon 1982). Microwaves can rewarm tissues at much higher rates than those methods depending on conductive, convective, and radiant heating.

Olsen and David (1984) exposed anaesthetized, hypothermic Rhesus monkeys to 13.56 MHz RFR using a helical coil. Specific absorption rates of approximately 5.5 W kg^{-1} were attained. Serum lactate dehydrogenase and creatine phosphokinase enzyme levels, associated with tissue damage, were elevated but this may have been due to anaesthesia or shivering effects. The increase of the enzymes was not of the magnitude that would be present if tissue injury had occurred. It was concluded that careful application of RF energy can be used to successfully rewarm hypothermic monkeys. One subject did however receive a superficial burn on the arm but this was attributed to the initial routing of the RF cable.

Successful rewarming of hypothermic mice used 2450 MHz MWR administered through a waveguide, at rates ranging from 0.04 - 0.65°C min^{-1} (Gordon 1982). Tail burning was seen in mice rewarmed at the lowest SAR of 209 W kg^{-1} as well as at the higher SAR of 1500 W kg^{-1}.

Radio frequency radiation rewarming methods were shown to be faster when compared to peritoneal lavage rewarming. The mean ± SD time required for rewarming dogs from a core temperature of 25°C to 30°C was 183 ± 79 min for lavage and 58 ± 13 min for microwave radiation. Serum enzyme levels were not significantly different between treatments, suggesting that no tissue damage occurred (White et al. 1985).

Radio frequency radiation has been successful in rewarming severely hypothermic animals. Olsen et al. (1987) showed that 13.56 MHz RFR rewarmed a hypothermic Rhesus monkey that had a temperature of 20°C and was undergoing cardiac collapse. Analysis of blood for hematological composition, proteins, and various enzymes showed no alterations due to RFR treatment. Latent tail burns were a common consequence of RFR; thus a method of shielding areas susceptible to overheating must be investigated.

Hypothermic dogs exposed to 13.56 MHz RFR using a cylindrical electrode antenna rewarmed faster than dogs rewarmed by warm humidified inhalation (White et al. 1987). The mean times to rewarm from a core temperature of 25°C to 30°C were 231 ± 3 min, and 106 ± 32 min for inhalation and RFR rewarming, respectively. This data suggests that RFR rewarming is an efficient, noninvasive technique for core rewarming in cases of hypothermia.

There are many factors that must be considered regarding the absorption of MWR and RFR (Table 1). The results of the rewarming studies show a promising future for the use of MWR in rewarming hypothermic animals. It would not be possible to achieve equivalent rewarming rates with non-microwave techniques as they may require temperatures up to 56°C that would cause protein denaturation and cell death (Gordon 1982).

THE DETERMINATION OF A SAFE AND EFFICIENT RATE OF REWARMING HYPOTHERMIC PIGLETS WITH 915 MHz MICROWAVE RADIATION

SUMMARY

Chilling, leading to hypothermia, is one of the major causes of death in small neonatal piglets. Microwave radiation, with its ability to penetrate tissue, can provide a very efficient means of delivering heat to the core of the animal. To determine a safe and time efficient rate of rewarming using a 915 MHz microwave unit, hypothermia was induced in 46 neonatal piglets weighing less than 1.25 kg each. Prior to suckling the piglets were dried, weighed, sexed, and their rectal temperatures were recorded. Their rectal temperatures were reduced to 25°C by placing the piglets in a 10°C cooling unit following a protocol approved by the University Animal Care Committee. Piglets were randomly assigned to be rewarmed at the rate of 0.5, 0.75, or 1.0°C min^{-1} using microwave radiation. After being rewarmed to 38°C, the piglets were returned to the sow and allowed to suckle. The rectal temperature of each piglet was recorded every 10 min until a stable temperature of 38°C was attained, in order to determine the temperature drop subsequent to rewarming, and recovery time. Body weights were recorded weekly for 28 days. Visual examination revealed no gross abnormalities in piglets rewarmed at any intensity. Initial birth weight and treatment rewarming rate had no significant ($P>0.05$) influence on the growth rate during the 28 d study period. Piglets rewarmed at 0.5, 0.75, and 1.0°C min^{-1} grew from 1.11 ± 0.03 kg, 1.02 ± 0.04 kg, and 1.01 ± 0.06 kg to 6.52 ± 0.23 kg, 6.74 ± 0.24 kg, and 6.55 ± 0.32 kg, respectively. There was no significant difference ($P > 0.05$) in the recovery times, the time piglets took to attain 38°C after rewarming, between treatment groups. It was concluded that the rewarming rate of 1.0°C min^{-1} was the most time efficient and provided a safe and effective treatment for hypothermic piglets.

Key Words: piglet, hypothermia, microwaves, rewarming

INTRODUCTION

Hypothermia has been determined to be the second highest cause of pre-weaning deaths in piglets (Edwards 1972; English and Morrison 1984). High pre-weaning mortality rates result in major losses to the producer in terms of feed, labour, and infrastructure (Ogunbameru et al. 1991; Newcomb et al. 1991). Hypothermia, leading to death is one of the most serious problems within the swine industry in relation to the issue of animal welfare (Expert Committee on Farm Animal Welfare and Behavior 1987).

Microwave radiation (MWR), having the ability to penetrate several cm into tissue and generate a rise in temperature, may be a means of treating piglet hypothermia. MWR operating at a frequency of 915 MHz has the ability to penetrate approximately 12.8 cm into tissues with low water content such as fat and bone, and about 2.5 cm into muscle which has high water content (Michaelson and Lin 1987).

There are reports that indicate that radio frequency (RF) and MWR used in the rewarming of hypothermic animals may cause burning especially in areas of poor circulation (Gordon 1982; Olsen and David 1984; White et al. 1987). It is not possible to accurately extrapolate safe rewarming rates or specific absorption rates (SAR) from one species to another; thus it is important to investigate a number of rewarming rates specific to each rewarming treatment and to each species.

The objective of this experiment was to determine a safe and rapid rate of rewarming hypothermic piglets using 915 MHz microwave radiation.

MATERIALS AND METHODS

Induction of Hypothermia

Hypothermia was induced in 46 newborn piglets weighing less than 1.25 kg each. Immediately after birth and prior to suckling, the piglets were dried, weighed, sexed, and their rectal temperatures were recorded using a digital rectal thermometer (Cole Parmer model 8110-20).

A protocol approved by the University Animal Care Committee to induce hypothermia was followed. Piglets were sprayed with water, placed in 56 x 42 x 22 cm individual pens with 1 mm mesh floors within a 10°C cooling unit, and removed when their rectal temperatures reached 25°C. All animals were then kept at room temperature (20°C) for a 20 minute holding period to monitor any drop in temperature following the cooling procedure. This holding period also simulated the more realistic farm situation where the piglet may not be immediately treated.

Microwave Equipment

Microwave radiation (MWR) was supplied by a MPS 915-500 CW generator (Cheung Laboratories Inc. Baltimore, ME) capable of supplving up to 500 watts (W) of continuous wave (CW) energy at 915 MHz. The generator was connected to a waveguide by an 80 cm 50 ohm coaxial cable (Figure 1). The 131 x 28 x 14 cm waveguide, designed by D'Ossone Canada Ltd. (Charlottetown, PEI) was constructed of stainless steel. The 16 x 64 cm oval lid of the waveguide had a mesh window which allowed visual inspection of the exposure chamber. A 1 L water load used to absorb any excess microwave radiation was situated in the waveguide at the opposite end from the antenna (Figure 1).

A Hioki Digital Hi tester, model 3181/3181.01 (Hioki E.E. Corp. Sakay Japan) was connected to the generator to monitor its power consumption. Forward and reflected power were measured with two Bird RF directional thruline wattmeters (model 43, Cleveland Ohio) attached between the antenna in the waveguide and the coaxial cable from the generator.

The microwave equipment was installed with several safety features. The waveguide lid had four safety switches that would not allow the magnetron to operate if the lid was not closed properly. The MW equipment was checked for leakage every day using a Microwave Survey Meter model 1600 (Holiday Industries Inc., Praire, MN).

Rewarming Procedure

Preliminary experiments rewarming saline phantoms, simulated piglet bodies, and piglet cadavers of different sizes and weights were used to test the MW equipment and determine appropriate rates of rewarming (Bate et al. 1992). At the beginning of parturition the first piglet weighing less than 1.25 kg was randomly allocated to one of the three rates of rewarming, therefore if the first piglet was rewarmed at 0.75 °C min^{-1}, the next piglet weighing under 1.25 kg was rewarmed at 1.0 ° min^{-1}.

Prior to rewarming, the piglets were wrapped in a 38 x 65 cm canvas blanket and secured in a uniform position with 2 velcro closures. The blanket was reinforced with 0.3 x 1 x 35 cm microwave transparent plastic strips sewn 5 cm apart. The wrapped piglets were placed in a 12 x 13 x 43 cm microwave transparent holding box within the wavegu de. A Luxtron fluoroptic temperature probe (model 750, Mountain View, CA) protected by polyethylene tubing (Clay Adams PE 160 ,ID 1.14mm, OD 1.57mm) was inserted 2.5 cm in the rectum to record temperature every 30 seconds.

All piglets were rewarmed until their rectal temperature reached 38°C. The piglets were then examined visually for thermal damage. Particular attention was given to the tail, ears, and eyelids where circulation is generally poor. The rewarmed piglets were placed back with the sow in a conventional farrowing crate with a 250 W supplementary heat lamp, in the creep area. The piglets rectal temperatures were recorded every ten min until a stable 38°C was attained. The piglets were weighed weekly until weaning at 28 days.

Statistical Analysis

The data were analyzed using the Statistical Analysis System Institute, Inc. (SAS Institute, Inc. 1985) software program to perform an analysis of variance and Duncan's test on all parameters measured (Table 1 and 2). The model was $Y_{ij} = \mu + \tau_i + \epsilon_{ij}$ where Y= dependent variable; μ= average, τ= treatment (the rate of rewarming), ϵ= error term (the difference in the total mean squares minus the treatment mean squares). Birth weight was used as a covariate in the analysis of piglet growth to weaning. The accepted level of significance for all analyses was $P < 0.05$. Reported values are all given as mean ± SEM.

RESULTS AND DISCUSSION

There were no differences ($P>0.05$) in cooling times between piglets rewarmed at different rates (Tables 1). There was a significant difference ($P<0.05$) between rewarming times, as well as the power levels used with the different treatments. Rewarming times for piglets rewarmed at 0.5, 0.75, and 1.0°C min^{-1} were 21.62 ± 5.73, 14.42 ± 4.38, and 10.12 ± 2.15 min, respectively. The increase in the rate of rewarming with the increased application of MWR suggest that the MWR delivered more energy to the core of the piglets.

Forward power levels used to rewarm piglets at the rate 0.5, 0.75, and 1.0°C min were 39.82 ± 1.63, 57.10 ± 2.70, and 63.60 ± 2.29 W, respectively with the corresponding reflected power levels of 10.11 ± 1.64, 15.35 ± 1.60, and 13.00 ± 1.91 W. The SARs for piglets rewarmed at the rates of 0.5, 0.75, and 1.0°C min^{-1} were 32.4 ± 3.26, 44.87 ± 5.21, and 58.89 ± 2.44 W kg^{-1}, respectively. Initial birth weight and treatment rewarming rate had no significant ($P>0.05$) influence on the growth rate during the 28 d study period. Piglets rewarmed at 0.5, 0.75, and 1.0°C min^{-1} grew from 1.11 ± 0.03, 1.02 ± 0.04, and 1.01 ± 0.06 to 6.52 ± 0.23, 6.74 ± 0.24, and 6.55 ± 0.32 kg, respectively during this period (Table 2).

Seven piglets died before weaning (Table 3). Of the four piglets which died in the first wk, two had been rewarmed at a rate of 0.5°C min^{-1}, one was rewarmed at 0.75°C min^{-1}, and the remaining piglet was rewarmed at the 1.0 °C min^{-1}. In wk 3, two piglets rewarmed at 0.75 °C min^{-1}, and one piglet rewarme at 1.0°C min^{-1} died. It was determined by post mortem examination that all piglets died due to crushing.

The majority of the piglets crushed were those with low birth weights. Piglets born with a relatively low birth weight are commonly referred to as runts. The runts may have received a low nutrient and energy intake during their fetal life (DePassille et al. 1988). It may have also been possible that the underdevelopment of the piglets was due to hypoxia(Hoy and Puppe 1992). Runt piglets may have been at a disadvantage within the litter as smaller piglets, with low energy reserves, often have difficulty competing for food, thus becoming weaker and more susceptible to crushing (Straw 1984; DePassille and Rushen 1989). The runt piglets may not have been able to obtain adequate colostrum, thus lowering their initial energy, protein, and maternal antibody intake. This would decrease their overall ability to cope with infections and stressors.

After rewarming with MWR and being placed back with the sow, the piglets' rectal temperature decreased by an average of 6°C. A decrease in rectal temperature has been reported in newborn piglets where their rectal temperature dropped approximately 2°C within 1 h after birth, then gradually rose back to the normal 38°C within 24 hours (Curtis 1983).

There was no significant difference between MWR treatments ($P>0.05$) in the time it took the piglets to maintain a stable 38°C rectal temperature (Table 1). The recovery time, however, was shortest for piglets rewarmed at the rate of 1.0°C min^{-1} at 68.30 ± 9.21 minutes.

The non-uniform characteristics of MWR absorption in living animals make it difficult to understand the exact heating pattern within the exposed body (Repacholi

1981). Thermal damage, often in the form of surface burns may occur if blood circulation is not capable of redistributing any excess heat which has occurred in certain areas of the body (Michaelson and Lin 1987). No evidence of thermal damage was observed in any of the rewarmed piglets. It appears that when exposed to MWR at a frequency of 915 MHz generating SAR as high as 58.89 $\pm$ 2.44 W kg^{-1}, the piglets are able to cope with the rapid temperature rise. The piglets, being rewarmed only to normal body temperature, were not expected to have to deal with any accumulation of excess heat. The lack of thermal damage suggests that the piglets' circulatory system was able to redistribute or dissipate any excess heat that may have been generated.

Tolerance to MW exposure decreases as the body temperature increases (Michaelson 1976). All piglets exposed to MWR in this experiment were suffering from induced hypothermia, thus increasing their capability to withstand substantial exposure to microwave radiation. The exposure of euthermic piglets to the same dose of MWR would probably have caused significant alterations in the physiological and behavioral responses as the piglets attempted to maintain homeostasis.

None of the rewarmed piglets exhibited any unusual behavior for the 28 d following the rewarming procedure. The theory that observed behavior effects are caused by the absorption of MWR within the CNS may suggest that the MWR used to rewarm the piglets did not directly overheat the central nervous system. There is, however, contradictory evidence to the assumption mentioned above. Galloway (1975) exposed monkeys' heads to 2450 MHz MWR for 2 min intervals to levels greater than 25 W. Such power levels produced severe burns and convulsions in some of the animals, but there were no significant changes in behavior in the non-affected animals.

It was concluded that the use of 915 MHz MWR to rewarm hypothermic piglets at the rate of 1.0°C min^{-1} caused no apparent physical or behavioral effects; thus this rewarming method seems to be safe and efficient in the treatment of piglet hypothermia. It may be appropriate to continue the investigation into the optimal rewarming rate using higher rates of rewarming such as 1.25 and 1.5°C min^{-1}, but caution should be used as the tolerance to MWR decreases as the absorbed power is increased.

Figure 1. Schematic diagram of the equipment used to rewarm hypothermic piglets with MWR: A) microwave generator, B) power meter, C) coaxial cable, D), forward wattmeter, E) reflected wattmeter, F), antenna, G) waveguide, H) lid, and I) the water load.

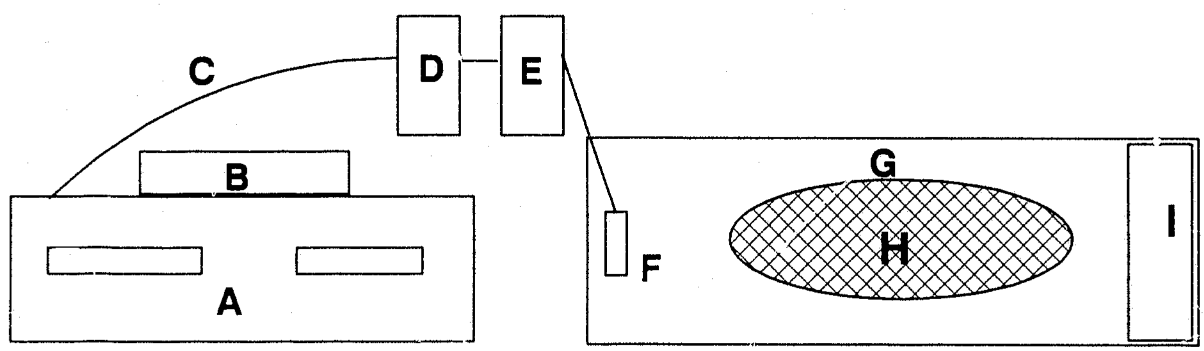
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Table 1. Parameters measured in cooling and rewarming piglets at different rates using MWR (mean ± SEM)

Parameter	Rewarming rate °C min^{-1}		
	0.5°C min^{-1} n = 16	0.75°C min^{-1} n = 18	1.0°C min^{-1} n = 12
Birth weight (kg)	1.11 ± 0.03^{a}	1.02 ± 0.04^{b}	1.01 ± 0.06^{b}
Temp. at birth (°C)	38.10 ± 0.29^{a}	38.40 ± 0.23^{a}	38.62 ± 0.22^{a}
Temp. after cooling (°C)	24.52 ± 0.20^{a}	25.00 ± 0.22^{a}	25.02 ± 0.23^{a}
Cooling time (min)	96.41 ± 11.22^{a}	88.30 ± 7.23^{a}	114.32 ± 18.70^{a}
Afterdrop temp (°C)	27.49 ± 3.34^{a}	34.21 ± 4.62^{a}	32.31 ± 5.60^{a}
Forward Power (W)	39.82 ± 1.63^{a}	57.10 ± 2.70^{b}	63.60 ± 2.29^{c}
Reflected Power (W)	10.11 ± 1.64^{a}	15.30 ± 1.60^{a}	13.00 ± 1.91^{a}
Rewarming time (min)	21.62 ± 1.43^{a}	14.42 ± 1.02^{b}	10.13 ± 0.60^{c}
Recovery time (min)	71.24 ± 10.10^{a}	72.82 ± 6.81^{a}	68.30 ± 9.21^{a}

Means within rows with different superscripts are significantly different ($P<0.05$).

Table 2. Growth rates from birth to weaning of piglets rewarmed by MWR at different rates (mean ± SEM)

	Rewarming rate °C min^{-1}		
Parameter	0.5°C min^{-1}	0.75°C min^{-1}	1.0°C min^{-1}
Birth weight (kg)	1.11 ± 0.03^{a} (n=16)	1.02 ± 0.04^{b} (n=18)	1.01 ± 0.06^{b} (n=12)
Weight week 1 (kg)	2.41 ± 0.11^{b} (n=14)	2.34 ± 0.13^{b} (n=17)	2.41 ± 0.15^{b} (n=11)
Weight week 2 (kg)	3.48 ± 0.11^{c} (n=14)	3.54 ± 0.19^{c} (n=17)	3.56 ± 0.23^{c} (n=11)
Weight week 3 (kg)	5.08 ± 0.22^{d} (n=13)	5.23 ± 0.24^{d} (n=16)	5.23 ± 0.32^{d} (n=10)
Weight week 4 (kg)	6.52 ± 0.23^{e} (n=13)	6.74 ± 0.24^{e} (n=16)	6.54 ± 0.32^{e} (n=10)

Means with different superscripts within columns are significantly different ($P<0.05$).

Table 3. Age and weights of piglets, rewarmed at different rates using MWR, that died during the trial

Rewarming Rate (°C min^{-1})	Birth weight (kg)	Age at death (days)	Death weight (kg)
0.5	1.16	3	1.57
0.5	1.08	5	1.71
0.5	0.87	16	3.00
0.75	0.86	4	1.3
0.75	0.93	18	3.20
1.0	0.82	3	1.29
1.0	1.24	18	4.41

There were no significant differences ($P > 0.05$) between treatments of parameters measured.

Table 4. Specific absorption rates for piglets rewarmed by MWR (mean ± SEM)

	Rate of Rewarming (°C min^{-1})		
	0.5°C min^{-1} n=16	0.75°C min^{-1} n=18	1.0°C min^{-1} n=12
SAR (W kg^{-1})	32.40 ± 3.26	44.87 ± 5.21	58.89 ± 2.44

There were no significant differences ($P>0.05$) between treatments of parameters measured.

EFFECTIVENESS OF REWARMING HYPOTHERMIC PIGLETS WITH 915 MHz MICROWAVE ENERGY VS. THE 250 W INFRARED HEAT LAMP

SUMMARY

Chilling, leading to hypothermia is one of the major causes of death in small neonatal piglets. To examine the effectiveness of using a 915 MHz microwave (MW) unit to rewarm piglets, hypothermia was induced in 39 neonatal piglets weighing less than 1.25 kg each. Prior to suckling, the piglets were dried, weighed, and their rectal temperatures recorded. Rectal temperatures were reduced to 25°C by placing the piglets in a 10° C cooling unit following a protocol approved by the University Animal Care Committee. Piglets were randomly assigned to be rewarmed by either the MW unit or the infrared (IR) method. The MW unit was programmed to rewarm at a rate of approximately 1°C min^{-1}, while the IR heating was provided by a 250 W infrared heating lamp placed 30 cm above the piglets. After being rewarmed to 38°C, the piglets were returned to the sow and allowed to suckle. To determine the magnitude of the temperature drop after rewarming, the rectal temperature of each piglet was recorded every 10 min until a stable temperature of 38°C was attained. Body weights were recorded weekly for 28 days. Rewarming time was shorter ($P<0.05$) in MW than IR rewarmed piglets (19.70 ± 6.32 vs 118.91 ± 5.00 min), respectively. Piglets were rewarmed by MW at a faster rate ($P<0.05$) than those rewarmed by IR (0.88 ± 0.05 and 0.12 ± 0.01°C min^{-1}) respectively. Treatment did not influence growth rate during the study period ($P>0.05$). Piglets rewarmed by IR grew from 1.11 ± 0.02 to 6.24 ± 0.03 kg during the trial while those rewarmed by

MW grew from 1.12 ± 0.02 to 6.19 ± 0.03 kg ($P<0.05$). It was concluded that the use of 915 MHz microwave radiation is a safe and more time efficient method for rewarming hypothermic piglets than using the conventional 250 W infrared heat lamp.

Key Words: piglet, hypothermia, microwaves, infrared, rewarming

INTRODUCTION

The use of microwave radiation (MWR), with its internal absorption characteristics, should theoretically provide a rapid method of rewarming hypothermic animals. Microwaves (MW) with a frequency of 915 MHz were able to penetrate saline (2.5 cm), blood (3.0 cm), muscle and skin (2.5 cm), lung (4.5 cm), and fat and bone (12.8 cm) (Michaelson and Lin 1987). The ability of MWR to penetrate to these depths should aid in the core rewarming of newborn piglets given that the average piglet trunk is approximately 8 cm in diameter. Core rewarming is important as it warms the blood and tissues close to the central vital organs, which may stimulate the movement of the rewarmed fluids to the extremities.

The 250 W infrared (IR) heat lamp is a traditional method used by many swine producers today to prevent and treat hypothermia. A problem with the IR rewarming technique is that it provides the piglet with only surface heating that imposes an increased metabolic demand in the periphery that the hypothermic liver cannot quickly supply as demonstrated in mice (Gordon 1982). Long rewarming times sometimes up to several hours resulting from IR heating, are detrimental to the piglet as those piglets that are not able to suckle early in life may not get enough colostrum and be deprived of passive immunity (Blecha and Kelly 1981; DePassille et al. 1988).

The objective of this experiment was to compare the effectiveness of using 915 MHz MWR to rewarm hypothermic piglets with the traditional rewarming method using the IR heat lamp as measured by survival, recovery time, and growth until weaning.

MATERIALS AND METHODS

Hypothermia to 25°C rectal temperature was induced in 39 neonatal piglets weighing less than 1.25 kg each in the same manner as described in the previous trial. All animals were then kept at room temperature for a 20 min holding period to measure any drop in temperature following the cooling procedure.

Piglets were alternately assigned to be rewarmed by either MWR or infrared radiation (IRR) with the first piglet randomly assigned to treatment. The same microwave generator and equipment as used in the first experiment supplied microwave radiation. The generator was programmed to rewarm hypothermic piglets at a rate of approximately 1.0°C min^{-1}, with SAR approximately 58 W kg^{-1}, because this rate was found to be a safe and efficient in the first experiment.

Infrared Rewarming

Infrared radiation was provided by a 250 W IR heat lamp. The lamp was suspended approximately 30 cm above the piglet which was held in a hammock within a cardboard rewarming box. The IR lamp provided an approximately 40°C environment for the piglet. Rectal temperature was monitored by a digital rectal probe (Cole Parmer model 8110-20) every ten minutes.

All piglets were rewarmed until their rectal temperatures reached 38°C. The piglets were then carefully examined for any signs of thermal damage especially in the areas of low circulation such as the ears, tail, and eyelids.

The rewarmed piglets were returned to the sow in a conventional farrowing crate which had a 250 W IR heat lamp in the creep area to provide supplementary heat for the piglets. Rectal temperatures were recorded every 10 min until it was stabilized when they reached 38°C. The piglets were weighed weekly until weaning at 28 days.

Statistical Analysis

The data were analyzed using General Linear Models of Statistical Analysis System Institute, Inc. (SAS Institute, Inc. 1985). Experimental design was a complete randomized block design with the restriction that only piglets weighing less than 1.25 kg would be rewarmed. The sows were considered as blocks and the rewarming with either MWR or IRR as the treatment. Therefore the model for the analysis was $Y_{ij} = \mu + \tau_i + ß_j + \epsilon_{ij}$ where Y= dependent variable, μ= average, τ represents the rewarming treatment, and ß represents the sows, and ϵ is the error term. Differences between means were measured by Duncan's multiple range test. The accepted level of significance for all analyses was $P < 0.05$. The values were all given as mean ± SEM.

RESULTS AND DISCUSSION

Mean cooling time was not significantly different ($P<0.05$) between MW and IR rewarmed piglets (Table 1). Rewarming time was shorter ($P<0.05$) in MW than IR rewarmed piglets with values of 19.70 ± 6.32 vs 118.91 ± 5.00 min respectively (Figure 1). The mean forward power level used for MW rewarmed piglets was 75.40 ± 2.60 W, while the mean reflected power was 20.40 ± 2.10 W. Specific absorption rate, calculated on the basis of temperature rise had a mean value of 58.81 ± 3.56 W Kg^{-1}. Piglets in the MWR group were rewarmed at a faster rate ($P<0.05$) than IR rewarmed piglets; 0.88 ± 0.05°C min^{-1} vs 0.12 ± 0.01°C min^{-1} respectively.

The basic principle of energy conservation requires that all MW energy absorbed by a physical body must be either converted into another form of energy or be reradiated. The MW energy absorbed by the piglets causes the vibration of the water molecules that cannot vibrate at the same frequency as the incoming MWR, and the resulting friction and heat released causes an increase in temperature within the tissues. Newborn piglets, having an approximately 80 % water content, are poor reradiators of electromagnetic energy (Michaelson and Lin 1987), thus most of the MW energy absorbed by the piglets must have been converted into heat.

The rapid rewarming action may have been due to the large deposition of MWR within the core of piglets that may have resulted in an increase of metabolic activity aided by an increase of blood flow from the rewarmed core to the extremities.

Piglets exposed to MWR took significantly longer ($P<0.05$) to attain a stable rectal temperature of 38°C after the rewarming procedure than those piglets rewarmed using infrared heat. The recovery times were 96.00 ± 12.12 and 23.16 ± 4.91 min, respectively (Figure 2).

The stabilization of body temperature after an initial temperature rise may be due to the adjustment of the local circulation, with vasodilation and the subsequent control of normal thermoregulation.

The piglets rewarmed by IRR had a substantially longer rewarming period in which the piglets gradually began to thermoregulate. In this case the time to total recovery is a more accurate parameter to measure whether the piglets regained adequate ability to thermoregulate. Piglets rewarmed by MWR took significantly ($P<0.05$) less time for total rewarming time than the piglets rewarmed by IRR with respective times of 115.70 ± 14.48 vs 142.10 ± 4.62 minutes.

The rectal temperatures of piglets has been reported to drop approximately 2°C after birth, then gradually rise back to 38-39°C within 24 to 48 h (Curtis 1983). There are a number of factors that contribute to this decline in body temperature: cooling evaporation from the wet skin, sparse hair coat, and the lack of insulation in the form of subcutaneous fat.

The temperature drop measured in this experiment was larger than those values reported by Curtis (1983). This may have been related to the piglets used in this study were all under 1.25 kg. Thus these smaller piglets with their high surface area to mass ratio would be expected to lose heat faster than heavier piglets. Calculating the area of a pig with the established formula: $A = 0.097W^{0.633}$, where A = surface area (m^2), W = body weight (kg) (Brody 1945, from Mount 1968) demonstrated that the surface area to body weight ratio for a 0.7 kg and a 1.25 kg piglet would be 0.11 and 0.08, respectively.

The drop in rectal temperatures may have caused the piglets to attempt to conserve heat by behavioral modifications such as huddling with their litter mates or the sow (McInnes and Blackshaw 1984). Piglets engaged in huddling activities may spend less time nursing thus depriving them of the colostrum needed for energy and thermoregulation. Once the piglet ingests adequate amounts of the energy rich colostrum, its metabolic rate increases and it attempts to thermoregulate (Curtis 1983, Benevenga et al. 1989).

Initial birth weight and treatment had no significant influence on the growth rate of the piglets during the 28 day study period ($P>0.05$). Piglets rewarmed by MWR grew from 1.12 ± 0.02 kg to 6.19 ± 0.03 kg, while those rewarmed by IRR grew from 1.11 ± 0.02 kg to 6.24 ± 0.03 kg (Table 2).

Three piglets, 1 IRR and 2 MWR died before weaning (Table 3). It was determined by post mortem examinations that all three piglets died due to crushing. The piglet rewarmed by infrared radiation weighed only 0.80 kg at 5 d of age when it was crushed. The piglets rewarmed by MWR weighed 2.72 and 3.85 kg at 3 wk of age when they were crushed.

Crushing remains one of the highest cause of pre-weaning deaths in piglets (Curtis et al. 1989). The use of farrowing crates was implemented to decrease the incidence of crushing, but there is not yet an ideal housing system that allows complete protection for the piglets. Low birth weight of the piglets places them at an immediate disadvantage within the litter. The piglet found crushed at 5 d of age, with its large surface to body mass ratio, may have had trouble maintaining euthermia. The piglet in a chilled and weakened state may not have been able to compete with its litter mates to gain adequate colostrum. Without gaining this necessary energy source, this piglet may have become hypoglycemic and too weak and lethargic to avoid being crushed by the sow.

The piglets found crushed at 3 wk of age also had low birth weights and may have succumbed to some of the same problems mentioned above. These two piglets with their slow growth rates may have been lacking adequate immunoglobulins, thus being more susceptible to stress and developed an overall lack of vigour.

One piglet rewarmed by MWR had a minor burn at the base of the tail. This piglet was one of the first to be rewarmed by MWR and it was noted that the tape used to secure the rectal fluoroptic temperature probe was too tightly wrapped around the tail and may have reduced the heat dissipating capacity of circulation. There were no more cases of tail burning after the tension of the tape was corrected.

In conclusion, it appears that the use of 915 MHz MWR provides a safe, faster, and more efficient method for rewarming hypothermic piglets than the surface heating supplied by the IR heating lamp. The implementation of the use of MWR in treating hypothermic piglets in a commercial operation may decrease mortality rates thus providing greater returns to the producer.

Table 1. Parameters measured in cooling and rewarming piglets rewarmed by MWR or IRR (mean ± SEM)

Parameter	Microwave rewarming n = 20	Infrared rewarming n = 19
Birth weight (kg)	1.11 ± 0.02[a]	1.12 ± 0.02[a]
Temp. at birth (°C)	38.22 ± 0.23[a]	38.51 ± 0.11[a]
Temp. after cooling (°C)	24.42 ± 0.22[a]	24.52 ± 0.22[a]
Cooling time (min)	81.70 ± 7.01[a]	73.60 ± 5.42[a]
Forward Power (W)	75.40 ± 2.60	
Reflected Power (W)	20.40 ± 2.10	
Rewarming time (min)	19.70 ± 6.32[a]	118.91 ± 5.0[b]
Recovery time (min)	96.10 ± 12.13[a]	23.22 ± 4.91[b]
Total Time (min)	115.70 ± 14.48[a]	142.10 ± 4.62[b]

Means with different superscripts are significantly different ($P<0.05$).

Table 2. Growth rates to weaning for piglets rewarmed with MWR or IRR (mean ± SEM)

Parameter	Microwave rewarming	Infrared rewarming
Birth weight (kg)	1.11 ± 0.02 (n = 20)	1.12 ± 0.02 (n = 19)
Weight week 1 (kg)	2.27 ± 0.12 (n = 20)	2.37 ± 0.12 (n = 18)
Weight week 2 (kg)	3.23 ± 0.20 (n = 20)	3.48 ± 0.19 (n = 18)
Weight week 3 (kg)	4.52 ± 0.29 (n = 18)	4.92 ± 0.22 (n = 18)
Weight week 4 (kg)	6.19 ± 0.32 (n = 18)	6.24 ± 0.28 (n = 18)

There were no significant differences ($P > 0.05$) between treatments in any of the measurements.

Table 3. Age and weight of piglets rewarmed by MWR or IRR, that died during the trial.

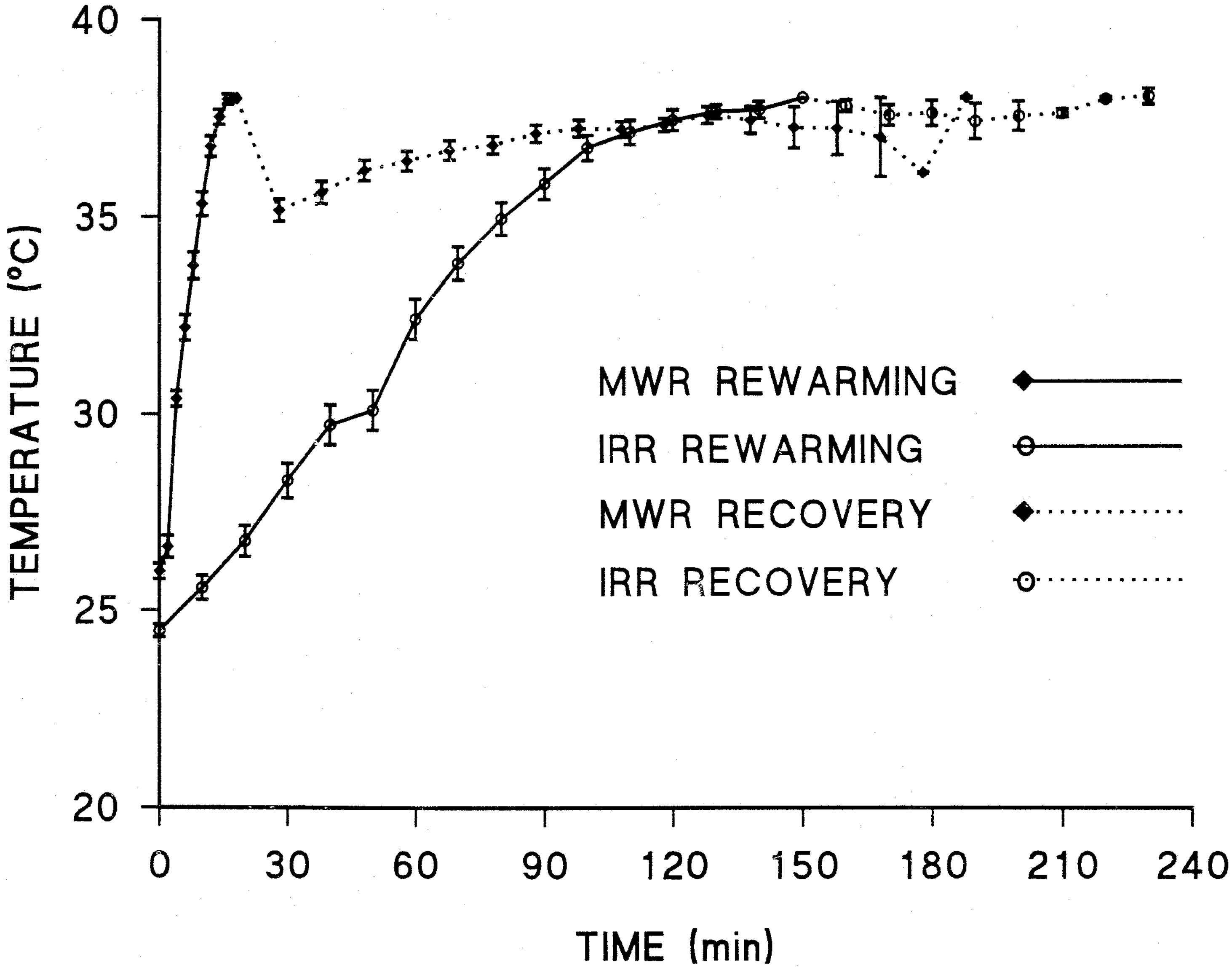
Treatment	Birth weight (kg)	Age at death (days)	Weight at death (kg)
MWR	0.78	21	3.45
MWR	1.17	20	2.72
IRR	1.02	5	0.80

There were no significant differences ($P>0.05$) between treatments in any of the measurements.

Figure 1. Rectal temperature of piglets during rewarming by MWR or IRR, and recovery after rewarming (mean ± SEM)

Rewarming time: The MWR rewarmed group is represented by 20 piglets from 0-10 min, and by 19, 14, 5, and 1 piglet at 12, 14, 16, and 18 min, respectively. The IRR rewarmed group is represented by 19 piglets from 0-60 min, and by 18, 15, 11, 8, 4, and 2 piglets at 70-100, 110, 120, 130, 140, and 150 min, respectively.

Recovery time: The MWR rewarmed group is represented by 20 piglets from 0-40 min, and by 17, 15, 13, 10, 9, 5, 4, 3, 2, and 1 piglet at 50, 60-70, 80, 90, 100-110, 120, 130, 140, 150, and 160-170 min, respectively. The IRR rewarmed group is represented by 19 piglets from 0-10 min, and by 8, 6, 3, and 2 piglets at 20, 30, 40-50, and 60-70 min, respectively.



40
35
30
25
20
TEMPERATURE (°C)
0
30
60
90
120
150
180
210
240
TIME (min)
MWR REWARMING
IRR REWARMING
MWR RECOVERY
IRR RECOVERY

REWARMING HYPOTHERMIC PIGLETS WITH 915 MHz MICROWAVE RADIATION VS. THE INFRARED HEAT LAMP : SHORT-TERM BIOLOGICAL EFFECTS

SUMMARY

Hypothermia was induced in 14 newborn piglets weighing less than 1.25 kg each. Prior to suckling, the piglets were dried, weighed, and their rectal temperatures recorded. The rectal temperatures were reduced to 25°C by placing the piglets in a 10°C cooling unit following a protocol approved by the University Animal Care Committee. The microwave (MW) generator was programmed to rewarm at a rate of approximately 1.0°C min^{-1}, while infrared (IR) rewarming was provided by a 250 W IR heating lamp. Piglets were rewarmed to 38°C and then returned to the sow where their temperatures were monitored until 38°C was maintained. Blood samples were taken at birth, after cooling, after rewarming, and at death. The piglets were sacrificed 48 h after rewarming and dissected for subsequent plasma and tissue analysis. Rewarming time was shorter ($P<0.05$) for MW than IR rewarmed piglets: 10.75 ± 4.60 and 101.80 ± 7.20 min, respectively. Plasma cortisol levels showed no significant differences ($P>0.05$) due to treatment within the four sampling times. Cortisol levels between times for each treatment were different ($P<0.05$). Plasma glucose levels from samples taken at birth, after cooling, and after rewarming were not significantly different between treatment groups. Rewarming treatment did not influence liver glucose and glycogen levels. The percentage area of the adrenal gland zones showed no significant difference ($P>0.05$) between treatment groups. It was concluded that rewarming hypothermic piglets with 915 MHz MWR does not appear to cause any detrimental effects, thus it may provide a safe and time efficient method for treating piglet hypothermia in a commercial farm situation.

Key Words: piglet, hypothermia, rewarming, biological effects

INTRODUCTION

There have been extensive investigations of the biological effects of microwave radiation (MWR) on animals (Lu et al. 1987; Michaelson and Lin 1987; Roberts et al. 1986) Much of this research involved the exposure of euthermic animals to MWR causing hyperthermic stress within the animal. The biological effects reported in such cases cannot be compared to those seen in hypothermic animals exposed to MWR in order to restore them to normal body temperatures.

The literature regarding MWR and radio frequency radiation (RFR) of animals contains many inconsistencies and many results are not comparable with each other. The difficulties in comparing the results of most studies are due to the differences in the MWR application, the methods of measuring MWR absorption, the frequency and duration of exposure, as well as the species of animals used and their initial body temperatures (Michaelson and Lin 1987).

The objective of this experiment was to compare the short-term biological effects in hypothermic piglets rewarmed by MWR and infrared radiation.

MATERIALS AND METHODS

Hypothermia was induced in 14 newborn piglets weighing less than 1.25 kg each. Six piglets weighing over 1.25 kg each were used as control animals that were neither cooled nor rewarmed. The methods used for the induction of hypothermia and the subsequent rewarming were the same as those described in experiment 1 with the exception of the blood sampling procedure. Blood samples were taken from the sub orbital sinus of the piglets at birth, after cooling, after rewarming, and at the time of sacrifice. The control piglets had a blood sample taken at birth and at sacrifice.

Hypothermic piglets were randomly assigned to be rewarmed either by MWR or by infrared radiation (IRR) from a 250 W heat lamp. The piglets were rewarmed until their rectal temperatures had reached 38°C. At this time the piglets were visually examined for any signs of thermal damage. Subsequently all piglets were placed back with the sow in the farrowing crate that was equipped with a 250 W IR heat lamp in the creep area to provide a source of supplementary heat. The rectal temperatures of the animals were monitored every 10 min until they maintained a steady temperature of 38°C.

The piglets remained with the sow for 48 h after birth. At this time they were sacrificed by CO_2 inhalation and exsanguination. The liver was removed, weighed, frozen in liquid nitrogen, and stored in a - 70°C freezer. The adrenal glands were removed, weighed, and fixed in 10 % buffered formalin solution and stored at 5°C. Blood samples were taken immediately after the time of sacrifice. The blood plasma was separated by centrifugation and frozen at - 20°C for later analysis of cortisol and glucose levels.

Liver Preparation

A 5 g sample of each frozen liver was removed by taking a uniform section of the lobes from each liver which were allowed to thaw at room temperature. The liver sample was then homogenized with homogenizing buffer (0.014 μM histidine and 0.002 M EDTA with a pH of 6.5) to make a 40 % liver homogenate. The homogenate was filtered through a 1 mm mesh sieve and divided into two aliquots. One aliquot was kept for glycogen determination and the other for the determination of glucose. All liver homogenates were stored at -75°C until the time of analysis.

Glycogen Analysis

Glycogen concentrations were measured by using a colorimetric reaction reported by Siu et al. (1970). A 50:1 dilution was made with distilled water and the 40% liver homogenate. A 20 μL sample of this homogenate was hydrolysed by the addition of 0.5 mL of phenol and 2.5 mL of sulfuric acid. Standard glycogen solutions of 5-200 mg mL^{-1} were treated in the same manner. Hydrolysis of the glycogen sample and standards were allowed to proceed for 3 hours. The absorbence was then measured using a Hewlett Packard spectrophotometer (Model 8452A) at a wavelength of 490 nm.

Glucose Analysis

Blood and liver glucose were measured using a Glucose Analyzer 2 (Beckman Inc.). The standard solution of 150/50 mg dL^{-1} glucose urea nitrogen was used to calibrate the analyzer. The reagent used was glucose oxidase supplied by Beckman Inc.

Cortisol Analysis

The analysis of plasma cortisol was performed using a Coat-a-Count cortisol RIA kit (Diagnostic Product Corporation, Los Angeles, CA). All the samples were run in one assay with an intra-assay coefficient of variation of 8.2 %.

Adrenal Glands

Previously fixed samples of the left and right adrenal glands from each piglet were cross sectioned and dehydrated in alcohol solutions following the procedure described by Luna (1968). The adrenal samples were then embedded into 3.0 x 2.5 cm paraffin blocks. A microtome was used to cut sections of adrenal tissue 6 μm thick from the block in order to prepare slides. The slides were prepared following the method of Luna (1968) using a hematoxylin and eosin regression stain preparation.

The image analysis equipment, consisting of a microcomputer, a camera, microscope, digitizer table, monitor, and the Bioquant software program (BQ System IV R & M Biometric, Inc. TN.) was used to evaluate the area of the adrenal slides. The slides were placed under the microscope and the image was projected onto the computer monitor from a television camera. The Bioquant software program is an image analysis program that can be used for application such as industrial quality control and biomedical research. The Bioquant program was interfaced with the image analysis equipment to provide a method to quantify the regions of the adrenal glands. The digitizer and mouse were used to measure the areas of the medulla, zona glomerulosa, zona fasciculata, and zona reticularis. The Bioquant program also calculated the means of the areas of each quadrant of the adrenal glands.

The Lotus software program was used to calculate the proportions of each adrenal gland using the information gained from the image analysis Bioquant system.

Statistical Analysis

The data was analyzed using the General Linear model of the Statistical Analysis System Institute, Inc. (SAS Institute, Inc. 1985) Experimental design was a complete randomized design. The model for analysis was $Y_{ij} = \mu + \tau_i + ß_j + \epsilon_{ij}$ where Y = dependent variable, μ = average, τ = rewarming treatment, ß = blocks, which were the sows, and ϵ was the error term. Analysis of variance with Duncan's multiple range test was used to determine differences between means in the parameters measured (Tables 2-6). The accepted level of significance was $P<0.05$. The values were all given as mean ± SEM.

RESULTS AND DISCUSSION

Mean cooling time was significantly shorter ($P<0.05$) for MW than IR rewarmed piglets with cooling times of 74.25 ± 7.30 and vs. 99.20 ± 8.06 min, respectively (Table 1). The difference seen in the cooling times may have been due to the piglets in the MWR group having a slightly lighter body weight, thus experiencing a faster drop in temperature than the heavier piglets in the IRR group.

Rewarming time was shorter ($P<0.05$) for MW than IR rewarmed piglets with respective values of 10.75 ± 4.60 and 101.81 ± 7.20 minutes (Figure 1). Forward and reflected power levels associated with the MWR rewarming method were 55.00 ± 1.60 and 11.01 ± 2.04 W, respectively.

Piglets rewarmed by IRR had a significantly shorter ($P<0.05$) post recovery time of 23.03 ± 6.00 vs. 61.87 ± 8.90 min for the MWR treated piglets (Figure 1). The total recovery time however was significantly shorter ($P<0.05$) for piglets rewarmed by MWR in comparison to IRR treated piglets with respective times of 72.62 ± 13.20 and 124.83 ± 13.20 minutes.

The total recovery time represents a more accurate parameter in assessing the piglets' overall ability to attain normal body temperature and thermoregulate. None of the piglets rewarmed with MWR or IRR showed any behavioral abnormalities after the rewarming procedure.

Cortisol serves in making glucose available for energy production and mobilization of energy stores needed by the body, especially in times of stress

(Kattesh et al. 1990). New born piglets respond to cold stress by the mobilization of liver and skeletal muscle reserves of glycogen. Significant increases in blood glucose were seen in piglets exposed to cold stress (Curtis et al. 1970). Changes in ACTH and corticosteroids levels in piglets exposed to stress in the form of changes in ambient temperature have been reported (Blatchford et al. 1978). Even small stressors such as the deprivation of a piglet of a food reward in an operant response study caused changes in ACTH and corticosteroid levels (Blatchford et al. 1978). Stressors activating the pituitary- adrenal system include housing, exercise, surgery, anaesthesia, and changes in temperature (Rijnberk and Mol 1989). The release of ACTH from the anterior pituitary induces the adrenal cortex to release corticoid hormones. The zona fasciculata and reticularis, regions which are involved in the production of cortisol, increase in width with prolonged ACTH stimulation (Ruckebusch et al. 1991; Munke et al. 1984).

The response of the pituitary adrenal system to the environmental stressors placed on the piglets was used as an indicator for actual stress the piglets experienced. There was no significant difference ($P > 0.05$) between cortisol levels of serum samples taken at birth, after cooling, and after rewarming from MWR and IRR rewarmed piglets; however a difference was found between treatment and control groups at time of sacrifice (Table 2). The circadian rhythm of cortisol in piglets may have influenced the differences in cortisol levels, as the piglets were sacrificed at different times. It appears by the cortisol data, that the MWR rewarming treatment did not cause the piglets any stress in excess of that seen in piglets rewarmed by the conventional IR heating lamp.

Analysis of plasma glucose levels showed no significant differences between treatment and control samples (Table 3). The elevated glucose levels at the time of sacrifice may be due to the killing process that induces a massive release of catecholamines (Mersmann 1974) or glucocorticoids (Bate and Grimmelt 1991). The glucose levels at sacrifice are possibly an exaggerated estimate of the true serum levels.

There were no significant differences ($P > 0.05$) due to treatment in piglet liver glucose and glycogen levels (Table 4). The medulla area of the adrenal gland produces catecholamines. The zona glomerulosa produce mineralocorticoids, and the zona fasciculata together with the reticularis produce glucocorticoids. The percentages of the adrenal gland zones were not significantly ($P > 0.05$) different between treatment groups of piglets (Table 5). It appears that rewarming piglets with 915 MHz MWR caused no detrimental biological effects. Thus the utilization of 915 MHz MWR in a farm situation could provide a safe and efficient method for treating piglet hypothermia which may aid in lowering of mortality rates and the subsequent improvement of swine productivity.

Table 1. Parameters measured in cooling, and rewarming of piglets rewarmed by MWR or IRR (mean ± SEM)

Parameter	Microwave rewarming n = 8	Infrared rewarming n = 6
Birth weight (kg)	1.05 ± 0.03[a]	1.19 ± 0.32[a]
Temp. at birth (°C)	37.49 ± 0.23[a]	38.05 ± 0.21[b]
Temp. after cooling (°C)	25.01 ± 0.01[a]	25.02 ± 0.01[a]
Cooling time (min)	74.25 ± 7.30[a]	99.20 ± 8.06[b]
Forward Power (W)	55.00 ± 1.60	
Reflected Power (W)	11.01 ± 2.04	
Rewarming time (min)	10.75 ± 4.60[a]	101.80 ± 7.20[b]
Post rewarming time (min)	61.87 ± 8.90[a]	23.03 ± 6.00[b]

Means with different superscripts are significantly different ($P<0.05$).

Table 2. Plasma cortisol levels (ng mL^{-1}) of piglets sampled at birth, after cooling, after rewarming with MWR or IRR, and at sacrifice (mean ± SEM)

	Cortisol (ng mL^{-1})			
TRT	**BIRTH**	**AFTER COOLING**	**AFTER REWARMING**	**AT SACRIFICE**
MWR	25.3 ± 2.1[a]	29.3 ± 5.6[a]	33.1 ± 3.7[a]	18.1 ± 9.7[a]
IRR	22.9 ± 2.5[a]	39.5 ± 9.9[a]	27.3 ± 4.4[a]	24.5 ± 1.8[a]
CONTROL	24.5 ± 1.9[a]			9.3 ± 1.9[b]

Means with different superscripts are significantly different ($P<0.05$).

Table 3. Plasma glucose levels (mg dL^{-1}) of piglets sampled at birth, after cooling, after rewarming with MWR or IRR, and at death (mean ± SEM)

	GLUCOSE (mg dL^{-1})			
TRT	**BIRTH**	**AFTER COOLING**	**AFTER REWARMING**	**AT SACRIFICE**
MWR	56.3 ± 2.7^{a}	104.6 ± 5.5^{b}	96.1 ± 10.2^{c}	119.0 ± 4.3^{d}
IRR	59.8 ± 2.6^{a}	107.4 ± 7.9^{b}	93.8 ± 3.4^{c}	126.2 ± 0.9^{d}
CONTROL	60.1 ± 3.9^{a}			114.7 ± 4.8^{b}

Means with different superscripts are significantly different ($P<0.05$).

Table 4. Liver glucose and glycogen levels of piglets rewarmed by MWR or IRR, and of control piglets (mean ± SEM)

TRT	LIVER GLYCOGEN ($mg\ g^{-1}$)	LIVER GLUCOSE ($mg\ g^{-1}$)
MWR (n=8)	69.2 ± 3.6	10.4 ± 3.8
IRR (n=6)	65.8 ± 4.8	13.2 ± 1.9
CONTROL (n=6)	62.8 ± 6.4	12.1 ± 2.0

There was no significant difference ($P > 0.05$) between treatments in any of the measurements.

Table 5. Percent area of the adrenal gland zones of piglets rewarmed by MWR or IRR, and control piglets (Mean ± SEM)

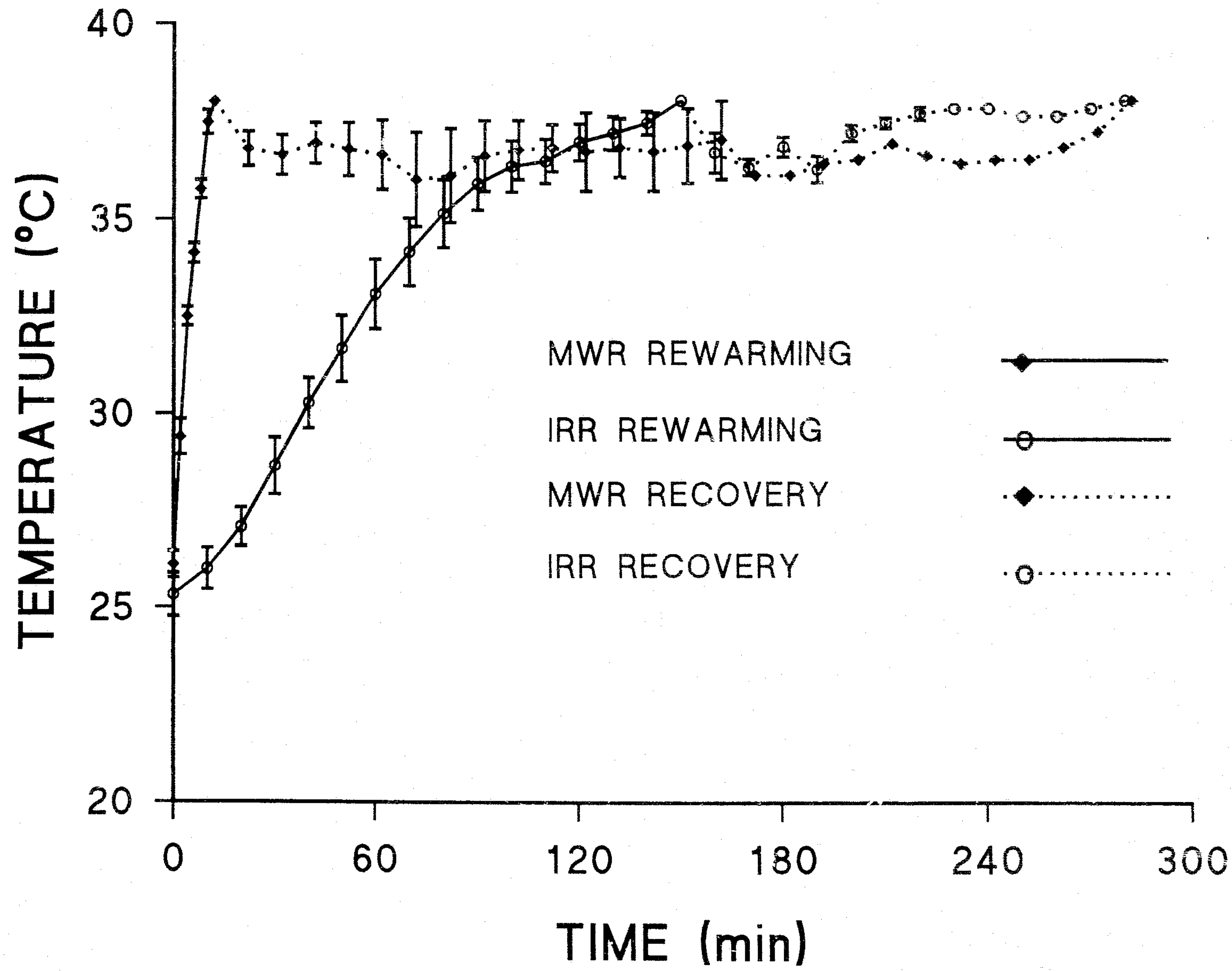
TRT	Medulla	Reticularis	Fasciculata	Glomerulosa
MWR	24.7 ± 2.5	5.1 ± 2.0	56.9 ± 2.2	13.2 ± 2.4
IRR	25.5 ± 2.0	6.9 ± 2.2	55.4 ± 3.1	12.1 ± 1.8
CONTROL	23.5 ± 2.3	5.5 ± 1.8	58.9 ± 3.5	12.1 ± 1.9

There was no significant difference ($P<0.05$) between treatments in any of the measurements.

Figure 1. Rectal temperature of piglets during rewarming by MWR or IRR and recovery time after rewarming (mean ± SEM)

Rewarming time: The MWR rewarmed group is represented by 8 piglets from 0-10 min, and by 3 piglets at 12 minutes. The IRR rewarmed group is represented by 6 piglets at 0-100 min, and by 5, 4, 3, and 2 piglets at 110-120, 130, 140, and 150 min, respectively.

Recovery time: The MWR rewarmed group is represented by 8 piglets from 0-10 min, and by 6, 4, 3, 2, and 1 piglet at 20-30, 40, 50, 60-150, and 160-270 min, respectively. The IRR rewarmed group is represented by 6 piglets from 0-10 min, and by 4, 3, 2, and 1 piglet at 20-40, 50-70, 80, and 90-130 min, respectively.



40
35
30
25
20
TEMPERATURE (°C)
0
60
120
180
240
300
TIME (min)
MWR REWARMING
IRR REWARMING
MWR RECOVERY
IRR RECOVERY

GENERAL DISCUSSION

The results of the three trials indicate that 915 MHz MWR may be a valuable method for treating piglet hypothermia. The rewarming rate determined in the first trial was much higher than most rewarming rates reported in studies rewarming dogs, monkeys, mice, and piglets (White et al. 1985; Olsen et al. 1987; Gordon 1982; Braithwaite et al. 1989). There are many factors that contribute to the absorption of MWR and subsequent rate of rewarming (Trial 3, Table 1). It is possible that many of these factors may have contributed to the ability to rewarm the piglets at such a rapid rate seen in this study. The frequency of the MWR is a key factor in the rate of power absorption within living tissues. The rate of rewarming using 915 MHz MWR in the current study was found to be almost 4 times higher than the rates observed when 2450 MHz MWR was used to rewarm hypothermic piglets (Braithwaite et al. 1989; 1993).

The use of the relatively low frequency of 915 MHz MWR with its higher penetration depths has advantages over the higher frequencies of 2450 MHz because the latter have lower penetration depths causing a more superficial absorption of MWR. The higher frequencies of MWR may cause slower rates of rewarming as well as more superficial burning and tissue damage as most of the heat is generated in the body surface.

It was determined in the second trial that MWR provided a significantly faster method of rewarming hypothermic piglets than the use of the 250 W IR heat lamp. The use of the IR heat lamp provides a surface heating that may take several hours to return the hypothermic piglet to euthermic conditions. Again, this can be related to the frequency of the red infrared light, being even higher than MWR, and therefore having less penetration. The long rewarming time observed in piglets rewarmed by IRR may reflect the time it took the piglet to begin to thermoregulate properly as determined by the stabilization of rectal temperature at euthermic levels.

The decrease in rectal temperatures observed after rewarming with MWR was higher than those observed in other studies where rectal temperatures were recorded 1 h after birth (Curtis 1983). The piglets in the three trials of this study were away from the sow for some hours during the cooling and rewarming process and therefore suckled much later than the piglets in the study conducted by Curtis (1983). Colostrum provides a rich source of energy to the piglet. Therefore the possible deprivation may have weakened the piglets, and decreased their resistance to cold stress.

It appears that MWR does not affect the growth and developmental phases of the piglets. Alterations in the growth and development of animals exposed to RF of MWR have been reported (Van Ummersen 1961), but this study involved the exposure of euthermic animals to levels of radiation that caused an overload of heat within the animal.

Piglets distribute themselves along a sow's udder in a teat order where each piglet chooses one or two specific teats. This order is established within a few hours or days and is sustained throughout the nursing period (DePassille and Rushen 1989; Hoy and Puppe 1992). Since the larger piglets in this study were used as controls and remained with the sow after birth, they may have been more aggressive in nursing and been able to ingest a larger amount of the high quality colostrum. The growth rate of the piglet is influenced mainly by the milk yield of the preferred teat (Hoy and Puppe 1992). The runt piglets, being smaller and generally weaker may not have been able to compete for a teat with high milk production. Therefore, it is possible that the runts were not successful in gaining adequate colostrum to provide them with adequate immunoglobulins and energy, thus lowering their overall immunity and placing them on a low plane of nutrition that resulted in a gradual loss of condition. Such a poor start in life linked with the continuing poor nutrition could explain the low growth rates and lack of vigour that resulted in the piglets being susceptible to being crushed (Dyck and Swierstra 1987). The nutritional quality of the colostrum decreases by approximately 50 % just a few hours after birth (Aumaitre and Seve 1978). Thus those runt piglets that may not have been able to nurse up to this point were being deprived of the high energy source.

The biological effects of animals exposed to MW and RF radiation have been studied extensively. However the number of confounding variables affecting the results make most studies difficult to interpret and compare. The restraining and temperature monitoring devices used in MWR exposure studies must be carefully selected due to the interaction of MW fields with the dielectric material within the exposure system. Studies using restraining and temperature measuring devices that cause any disruption of the electromagnetic waves render the results non-comparable with the more carefully controlled studies. The use of thermocouples and thermoresistors within tissue during irradiation cause perturbation of the field surrounding the sensor, thus altering the temperature of the tissue (Michaelson and Lin 1987). The microwave transparent plexiglass holding box and the fluoroptic temperature probe used in this study are both materials that cause insignificant perturbation of the electromagnetic fields within the waveguide; therefore, the data collected using this system provided a more accurate estimate of the absorption of the MWR by the rise in rectal temperature.

Most of the studies that reported detrimental effects when animals were exposed to MW or RF radiation used euthermic animals and their results supported the theory that the effects of MWR exposure were primarily a response to hyperthermia or the altered thermal gradient within the body.

The use of anaesthetic to restrain the euthermic animals exposed to electromagnetic radiation may also be a factor in the successful rewarming as the animal under anaesthesia may experience a decrease in its ability to dissipate heat (Michaelson and Lin 1987). None of the piglets used in these studies were anaesthetized or sedated. Therefore it is possible that these animals had a greater ability to dissipate and redistribute any excess heat within the body in comparison to animals that were anaesthetized (Olsen and David 1984); hence this study better reflected the normal physiological state of the piglets.

The evaluation of some of the short-term biological effects of MWR on the piglets determined in trial 3 revealed plasma cortisol levels at birth which were comparable to those found in other studies (Kattesh et al. 1990; McGinnis et al.

1981). This peak concentration of cortisol observed at birth may have been attributed to its involvement in the initiation of parturition similar to that found in other studies (Kattesh et al. 1990). The removal of newborn piglets from the sow has been shown to cause an increase in plasma cortisol levels of the piglets (McCauley and Hartmann 1984). This, together with the actual blood sampling procedure, may explain the high levels of cortisol measured in the piglets of this study. The subsequent drop in cortisol levels may have represented the half life of cortisol which is less than 2 hours (MacDonald 1988). The subsequent stabilization of the cortisol levels may have reflected the piglets' changing metabolism and/or the synthesis of cortisol by the piglet (Kattesh et al. 1990).

The levels of glucose and glycogen in the liver were found to be similar between MWR and IRR treatments. This lack of difference suggests that there was no alteration in the liver's enzymatic ability to generate glucose from stored glycogen or to store excess glucose as glycogen as a result of the rewarming system. It appears that neither the length of exposure nor the intensity of the MWR used to rewarm the hypothermic piglets was sufficient to disrupt normal liver function. Prolonged ACTH release from the anterior pituitary induces the adrenal cortex to release corticoid hormones which increase energy supply to tissues. Such stimulation of the adrenal cortex by ACTH would cause the widening of the zona fasciculata and reticularis which act as unit in the production of cortisol (Ruckebusch et al. 1991). The exposure of the piglets in this study was not longer than 20 min, therefore possibly limiting the stimulation of the adrenal cortex and causing no changes in the cortisol production.

Changes in adrenal activity would likely cause an increase or decrease in the adrenal zones (Munck et al. 1984). Piglets rewarmed by MWR showed no differences in the percentage of the different zones of the adrenal gland in comparison to IRR rewarmed and control piglets. This suggests that exposure of the piglets to MWR was not long enough or at a high enough power level to cause prolonged adrenal stimulation or initiation of changes in adrenal zones.

The lack of detrimental biological effects seen in these rewarming studies may be attributed to the fact that the animals used in this study were hypothermic and were exposed to only the amount of MWR needed to rewarm them to euthermic levels with a rectal temperature of 38°C.

The applicator used to expose the animal to MWR may have an effect on the type of disruptions that are seen in animals exposed to the same frequency. The whole body exposure of the piglets to radiation within the waveguide did not appear to have caused any detrimental effects unlike those reported from exposing animals to near field radiation (Michaelson and Lin 1987). The incidence of cataract formation and ocular damage has never been reported in studies using far field or whole body exposure or in hypothermic animals (Michaelson and Lin 1987).

The theory that observed behavioral effects are caused by the absorption of the MWR within the CNS may suggest that the MWR used to rewarm the piglets did not directly overheat the CNS to the point of modifying its normal function. Perhaps the short exposure time used in this study and the intensity of MWR was not enough to alter the system. The lack of behavioral effects observed in MWR rewarmed piglets may also have been due to the initial state of hypothermia and the subsequent exposure to MWR only until the piglet reached its normal body temperature. Most of the studies reporting behavior disturbances involved the exposure of euthermic animals to MWR that caused hyperthermia and subsequent behavior changes in an attempt to maintain homeostasis (Michaelson and Lin 1987). A different response may be expected if MWR was applied to euthermic piglets at the SAR used in this study. The euthermic animals would soon have been heated to temperatures well above their normal temperatures, and it could have been difficult for the animal to dissipate the excess heat fast enough to maintain homeostasis.

The rapid rewarming rate allowed with MWR appears to result in a high deposition of energy throughout the core of the piglet. This effective core rewarming appeared to stimulate the flow of rewarmed fluids throughout the body, resulting in the rapid rewarming rate observed. The use of MWR is much more effective than the conventional IRR as it does not depend entirely on conductive or convective transfer of heat from the warm to cool tissues as is the situation with the infrared heating method.

This study demonstrates that the utilization of 915 MHz MWR is a safe and more efficient method for rewarming hypothermic piglets than the conventional 250 W infrared heat lamp. The rewarming rates used in this study were chosen in response to reported rates in other animal rewarming studies (Olsen et al. 1987; Gordon 1982) and in respect to preliminary trials performed on phantom and dead piglets before this study was started. The use of severely hypothermic piglets in this study prompted the use of rewarming rates higher than most of the reported rates from studies using less hypothermic animals. The maximum rate of rewarming using MWR that the piglet could tolerate without any adverse affects was not determined in this study. Further investigations into the most efficient rate of rewarming should be performed using the highest rate found in this study as a base, and with increases of 0.25 to 0.5 min^{-1}. The faster the piglet is safely rewarmed, the sooner it can be returned to the sow to suckle to obtain the rich colostrum and immunoglobulins.

The efficiency of rewarming in a short time is also extremely important to the producer, since less time and money spent on rewarming will aid in energy conservation and decrease in labor required for the procedure.

A study performed in Western Canada reported that sixty-five percent of the total energy consumption used on farrow to weanling operations was used for heating, and 78% of that was provided by infrared heat lamps, (Barber et al. 1989) with a portion of that being used for rewarming hypothermic piglets.

There could be considerable economical savings in energy utilization when using a MWR system instead of the 250 W heat lamp. An ideal microwave system should operate at approximately 60 % efficiency; therefore in order to generate 50 W it would use 84 W. The prototype microwave generator used in this study used approximately 130 Wh to rewarm hypothermic piglets at a rate of 1.0°C min^{-1}. This generator operated at only 38 % efficiency, and yet it used significantly less power than the infrared heat lamp that used an average of 424 Wh to rewarm the hypothermic piglets.

The electrical cost of rewarming one piglet by MWR or IRR would be 1.4 ¢ and 4.5 ¢, respectively with the current price of electricity at 10.5 ¢ KWh^{-1}.

Magnetron replacement cost is the only other ongoing cost for the microwave system. Replacement costs were estimated at 10-15 ¢ per operating hour for a 100 W output tube (Tranquilla 1993, personal communication). Replacement cost per rewarmed piglet would be approximately 2.5 cents. Electrical and magnetron replacement cost per rewarmed piglet is 3.9 cents. This cost appears extremely insignificant in regards to saving a newborn piglet that costs approximately $ 20, and would eventually be marketed at approximately $150 per 100 Kg.

In conclusion it appears that there is potential for the use of MWR in commercial swine operations. The implementation of a rewarming unit using MWR may help to decrease the mortality rates due to hypothermia while assisting in animal welfare by eliminating the prolonged suffering of the chilled piglets. The decrease in mortality rates and energy costs would in turn provide higher returns to the swine producer.

Future research should be conducted to compare the MWR to the IRR rewarming systems in a commercial swine operation in which mortality rates could be monitored on a larger scale.

GLOSSARY

Absorption: Attenuation of the electromagnetic wave due to its energy being dissipated or converted to another form of energy such as heat.

Absorber: A material which absorbs MWR and converts its energy into heat.

Ampere: The standard unit for measuring the strength of an electric current; rate of flow of charge in a conductor or conducting medium of one coulomb per second.

Amplitude: The peak strength of a periodic wave.

Anechoic chamber: An enclosed cavity that is designed to minimize reflected energy. The walls of the cavity are lined with material having high absorbing properties.

Antenna: A device used to radiate or receive electromagnetic waves.

Applicator: A device used to deliver electromagnetic radiation, usually in the form of an antenna.

Applied Force: A force directed to a specific object or area.

Attenuation: Decrease in magnitude of current, voltage, or power of a signal in transmission between points.

Coaxial Line: A transmission line consisting of one conductor that completely surrounds the other, the two being coaxial and separated by a continuous solid dielectric or by dielectric spacers. A coaxial line has no external field and is not susceptible to external fields from other sources.

Conductivity (σ): A measure of the materials ability to conduct electrical and magnetic energy.

Conductor: A material which conducts electricity.

Convection: The transfer of heat due to differences in the density or temperature of the parts of the medium.

Continuous Wave (CW): Continuous fixed frequency wave.

Current: The electrical flow of electric charge in a conductor or medium between two points having a difference in potential, generally expressed in amperes.

Cycle: One complete oscillation of a wave.

Dielectric: A class of materials which are generally non-conductive to electrical current.

Dielectric Constant: A measurement of the ability of a material to support an electric field.

Direct Contact Antenna: An antenna that directly touches the object that is to be irradiated.

Dipole Antenna: A center-fed antenna excited in such a way that the standing wave of current is symmetrical about the mid-point of the antenna.

Electromagnetic Energy: The energy stored in an electromagnetic field.

Electric Field: A region of electromechanical force due to an electric charge.

Electromagnetic Source: The object or origin from which electromagnetic energy radiates from.

Electromagnetic Spectrum: The complete range of frequencies of electromagnetic waves from the lowest to the highest frequency including, in order, radio, microwave, infrared, visible light, ultraviolet, X-ray, gamma ray, and cosmic ray waves.

E Vector: The magnitude and direction of the electrical force.

Electromagnetic Wave: A wave characterized by variations of the electric and magnetic fields.

Electron Volt: The unit of energy equal to that attained by an electron falling unimpeded through a potential difference of one volt; 1.602×10^{-12} erg.

Emissivity: The relative ability of a surface to radiate energy as compared to that of an ideally black surface under the same conditions.

Far fields: Electromagnetic fields that exist at distances greater than a few wavelengths away from the source. In far fields the electric field vector E (volts m^{-1}) and the magnetic field vector H (amperes m^{-1}) are perpendicular to each other and to the direction of wave propagation. The power density of the spherical waves varies as $1/r^2$ (r = distance from the electromagnetic source).

Forward Power (FP): Power flowing into the load from the electromagnetic source.

Frequency: The number of positive or negative peaks of a travelling wave that move past a fixed point in one second. It is expressed as oscillations or cycles per second . The unit for frequency is hertz (Hz). The equation for calculating the frequency is $f = c/\lambda$; where f = cycles per second (Hz), c = the distance light moves in one second ($2.998 \times 10^8\ m\ s^{-1}$), and λ = wavelength (m).

Ground: A conducting body, such as the earth whose potential is taken as zero and to which an electric circuit can be connected.

Ground Potential: The electrical potential of a ground conductor.

Guided propagation: The e/m wave is confined in or near a physical structure such as in a waveguide or transmission line.

Heat: A form of energy whose effect is produced by the accelerated vibration of molecules causing the mechanical energy to be converted to heat.

Heat Capacity: The amount of energy required to raise the temperature of 1 gram of material $1\,^{\circ}C\ min^{-1}$.

Hertz: The unit used to express the frequency of electromagnetic energy.

H Vector: The magnitude and direction of the magnetic force.

Hot Spots: The result of an accumulation of standing waves that cause an excess of heat to be generated within the tissue.

Incident Power: The power transmitted towards an object to be irradiated, measured at the point of contact with the object.

Induction Coil: A coiled electrical conductor used to establish a concentrated magnetic field.

Infrared Energy: Energy with frequencies above the region of microwave energy, having wavelengths between 0.75 - 1000 μm.

Irradiation: The exposure of an object to radiation.

Impedance: The property of a medium to resist current flow. The ratio of electric field (E) / magnetic field (H) expressed in ohms. The impedance of air is 377 ohms.

Ionizing Radiation: Radiation which has sufficient photon energy to displace an electron from its orbit.

Irradiation (whole body): The exposure of the entire subject to incident electromagnetic radiation.

Irradiation (partial body): The exposure of only part of the subject to incident electromagnetic radiation.

ISM Frequency Band (Industrial, Scientific, and Medical Band): Equipment operating at frequencies within this band are allowed to be used for ISM purposes with no licence or power restrictions as long as they are operated within safety limitations. Frequencies of 2450 MHz and 915 MHz are both within this band.

Joule: The unit used to express the amount of work or energy produced.

Light: A form of electromagnetic radiation that produces energy in a visible form.

Load: The object that is to be irradiated placed within the exposure device, or an additional water load that absorbs any excess electromagnetic energy.

Loss tangent ($\tan\delta$) = $\sigma/\omega\epsilon$: Where σ is the conductivity of the medium, ω is 2π times the frequency, and ϵ is the dielectric constant. A perfect dielectric, with zero conductivity would have a loss tangent of zero. A material with perfect conductivity would have an infinitely large loss tangent.

Magnetic Field: A vector function of a field defined by magnetic induction.

Magnetron: A device used to generate electromagnetic energy. The magnetron can produce up to 50 kW at 55-75% efficiency and may operate at frequencies up to 4 GHz. The electronic tube operates as a simple diode and modulation is obtained by applying voltage to the cathode with the anode at ground potential. Tunable (CW) magnetrons are used in electronic applications. Fixed frequency magnetrons are used as microwave heating sources.

Magnetic Resonance Imaging: The magnetic resonance produced by strong static magnetic fields, a time varying magnetic field, and RF pulses. It is used to image body tissue and monitor body chemistry.

Matching: When two media have equal impedances they are said to be matched. All of the energy transmitted from the first media will be transmitted into the second medium with very little reflection at the boundary of the two media. If the two media are mismatched then some of the energy will be reflected at the boundary and the remainder will be transmitted into the second medium.

Microwaves: Electromagnetic waves in the frequency band range between 300 MHz and 300 GHz.

Modes: The pattern normally used to describe the distribution of electromagnetic energy in a waveguide or cavity.

Mode Stirrers: Metal fan blades that rotate to disrupt the electromagnetic field inside a cavity in order to provide as many modes as possible.

Modulation: The superposition of an information signal upon a carrier wave.

Multimode Cavity: A shielded enclosure in which the MWR or RF waves are transmitted in as many modes as possible to provide a uniform field. The domestic MW oven is an example of a multimode cavity.

Near fields: Electromagnetic fields that exist within a few wavelengths from the source. E and H are not necessarily perpendicular to each other and are a function of the distance from the source; $1/r^2$, and $1/r^3$.

Nonionizing Radiation: Radiation which does not have enough photon energy to displace an electron from its orbit.

Oscillations: The regular variation of a wave from its minimum to maximum amplitude.

Ohms: The unit used to express electrical resistance, equal to the resistance of a circuit in which the electromotive force of one volt maintains a current of one ampere.

Period: The interval between two identical points or successive cycles of a periodic wave.

Permeability: Characteristic of a material in a magnetic field. The ratio of magnetic flux density in a material compared to that which would be present in air under the same applied force.

Phase: The property of an electromagnetic wave used to describe its instantaneous amplitude or position with respect to a reference origin. One complete period occupies 2π radians of a phase.

Phase velocity: The velocity at which a point of a given phase moves in a travelling wave ($m\ s^{-1}$).

Photon Energy: Quantum of electromagnetic energy having both particle and wave behavior; no charge or mass, but posses momentum. It is the energy of light, X-rays, gamma rays, and is carried by photons.

Plane Waves: The equiphase contours of radiation emitted by a transmitting antenna appear as waves in a plane at distances far from the source. Both the electrical and magnetic fields lie in the plane of the wavefront.

Poor Coupling: This occurs when two mediums have different impedances, thus there is a large reflection of the transmitted wave at the interface of the mediums.

Power: Mean power, work or energy divided by the time in which this work or energy was produced or absorbed. The Watt (W) is the unit for power.

Power density: The time rate of energy flow per unit area across a surface. Power density is an expression of exposure in terms of incident power per unit area described by the units $W\ m^{-2}$.

Protracted Irradiation: Exposure to radiation for a prolonged period of time.

Pulsed Wave: A wave transmitted at specific intervals; there is not a continuous flow of energy.

Radiation: The process by which energy is sent out through space from atoms and molecules as they undergo internal change.

Radioactive: The ability to giving off radiant energy in the form of particles or rays by the spontaneous disintegration of the atomic nuclei of certain elements.

Radiofrequency: Electromagnetic radiation having frequencies in the range of 10 KHz-300 MHz.

Reflection: When microwave radiation propagated in one medium impinges on a second medium having different electromagnetic properties, partial reflection occurs at the boundary between the two mediums. Some of the incident radiation may be transmitted into the second medium.

Reflected Power (RP): Power reflected from the interface between different media.

Resistance: The property of a conductor by which it opposes the flow of electrical current, resulting in the generation of heat in the conducting material.

Resonant Mode: The mode in which the frequency of the transmitted energy is near that of the exposed bodies natural frequency.

Shielding: The use of a material to prevent energy absorption into a specific part of the objects irradiated by using highly conductive material to shield the area from the electromagnetic radiation. The shielding material should be at least one to two skin depths thick in order to attenuate and reflect most of the energy and prevent it from reaching the protected areas.

Signal: The electromagnetic impulse that is transmitted or received.

Skin Depth: The depth of penetration at which the field strength has dropped to 1/e of its initial value. e = base of natural logorithim.

Specific Absorption Rate (SAR): The amount of energy absorbed per unit mass. It is expressed in Watts per kilogram (W kg^{-1}). SAR is dependent upon a number of factors such as the incident radiation, body geometry and orientation, and the materials dielectric properties.

Specific Heat: The amount of heat required to raise the temperature of water 1°C min^{-1}.

Standing Wave: The result of two signals moving in opposite direction along the same transmission path.

Thermometer: An instrument used for measuring temperatures.

Thermometry: The measurement of temperatures.

Time Varying Magnetic Field: An electromagnetic field in which the amplitude of the electric and magnetic field components vary cyclically with time, usually according to a sinusoidal variation sin wt, where $\omega = 2\pi f$, t = time.

Ultra Violet Radiation: Radiation with wavelengths between 4 - 400 nm.

Unguided propagation: A wave which is not guided by any physical restraints.

Volt: The unit of electromotive force or difference in potential between two points in an electric field that requires one joule of work to move a positive charge to the point of lower potential to the point of higher potential.

Voltage: Electromotive force, or difference in electrical potential, expressed in volts.

Watt: The unit for electrical power, equal to one joule per second or the power developed in a circuit by a current of one ampere flowing through a potential difference of one volt.

Wave: The modification of the physical state of a medium which is propagated as a result of a local disturbance.

Wave decay: The proportional decrease in the power of the wave as it travels through a medium.

Waveguide: A metal enclosure in which electromagnetic energy is transmitted.

Wavelength: The distance between identical points o[illegible]o successive periodic cycles of a wave.

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