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Measurements of peripheral and deep body temperature in cattle – A review

Dorota Godyń[a,*], Piotr Herbut[b], Sabina Angrecka[b]

[a] Department of Production Systems and Environment, National Research Institute of Animal Production, Krakowska 1, 32-083 Balice/Krakow, Poland
[b] Department of Rural Building, University of Agriculture in Krakow, Al. Mickiewicza 24-28, 30-059 Kraków, Poland

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ABSTRACT

Automation of the measurement of the physiological and behavioural parameters of livestock has become an important goal for both scientists and farmers. Accurate data and knowledge about farmed animals, especially in cattle breeding, are needed. Proper early diagnosis of a cow's health status in real time allows for preventing the development of infection, oestrus detection and leads to reduced environmental stress. Thus, it contributes to more effective herd management. Among the physiological parameters, body temperature and its fluctuations are key indicators of health and well-being in animals. Currently, along with the development of technical solutions and their implementation, increasingly more attention is being paid to the continuously measurement of body core and peripheral temperature in animals. Recently there has been an increased number of publications devoted to this subject. However, there is a need to systematise this knowledge as these studies have had different purposes, have been performed in various environmental conditions, and the measurements were taken using different methods and equipment. As such, the results obtained by the different authors often may not be comparable. For this reason, this paper has two main purposes: to present the most widely used continuous methods of peripheral and body core temperature measurement, and to show its references values which characterise the individual locations of the cattle body in thermoneutral ambient. An analysis of the professional publications regarding measurements of peripheral and deep body temperature led to the conclusion that these methods have high research and diagnostic potential. However, it is necessary to standardised research to enable better and more comparable results, including among others; different cattle groups, animal age, health and environmental conditions.

1. Introduction

The monitoring of animal health and welfare is a key aspect for breeders and producers. One of the most important indices of animal well-being is the body core temperature. Nowadays, for both human and animal research, the application of various technologies to measure skin surface and body core temperature has been gaining in popularity. A health deterioration and other physiological disturbances can be detected much earlier with these technologies than with traditional methods. An example of such an application is the continuous temperature measurement. This procedure applies primarily to the internal temperature of the body; however using the devices for monitoring shell temperatures is also common.

Continuous measurements of body temperature may be an essential factor in effective control of cattle herds. Apart from the monitoring of the health state of an animal, this type of measurement can be of key importance in preventing the outcomes of thermal stress. It may also be an ideal indicator of the effectiveness of the applied cooling systems as

well as other strategies preventing overheating in animals. Other applications of these technologies may lead to better diagnostics of oestrus or other physiological conditions reflecting the animal welfare, which indirectly may affect the profitability of the production. Bearing in mind the differences between equipment used to measure temperature, as well as the different breeds, physiological stages and environmental conditions under which an animal is kept, it is worth presenting the different applications of temperature measuring devices used in recent studies on cattle.

The objective of this paper is to present and systematise the current state of knowledge of the most widely used methods of peripheral and body core temperature measurement in cattle. Particular attention has been paid to the continuous monitoring of temperature and its values which characterise the individual locations of the animal body.

2. Body temperature regulation

There are autonomic and behavioural temperature regulatory

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mechanisms in homoeothermic animals. Heat production resulting from metabolic processes must be exchanged within a body (across cellular and vascular membranes), and between a body and its environment. In mammals under thermoneutral conditions, these processes are kept in balance; however, it is always a dynamic equilibrium resulting from continuous and variable metabolic heat production and convective heat transport through tissues (Taylor et al., 2014). Conditions of the surroundings in which an animal makes a minimal metabolic effort to maintain a stable internal temperature, where it is only the skin temperature that fluctuates and losses of heat via evaporation are kept to a minimum, define the zone of thermal comfort (Curtis, 1983). Cows are well able to adapt to changing temperature and humidity conditions throughout the year (Kadzere et al., 2002). This can be confirmed by the relatively wide range of neutral temperatures established for dairy cattle. Fluctuations of temperature within a range of − 0.5–20.0 °C (West, 2003) is generally accepted as a thermoneutral value that does not significantly influence physiological or behavioural changes among cows. The level of air temperature generally accepted as 25.0–26.0 °C (West, 2003), or 24.0–27.0 °C (Brouček et al., 2009) is the so-called upper critical level, above which the cow's welfare is disturbed.

During periods of excess heat or cold in the surroundings, homeostatic mechanisms of the body are activated to re-establish the thermal status of the internal environment or to regulate it within physiologically acceptable limits (Werner et al., 2008). The processes of thermogenesis and mechanisms to eliminate excess heat undergo regulation. The centre of it is located in the hypothalamus. It receives information on the fluctuations of temperatures in both surface and deep tissues of the body as these receptors are components of the thermal feedback loops. While the feedback from deep thermoreceptors has a greater impact on the organs taking part in body-temperature regulation, the skin receptors' feedback plays an important role during adaptation processes (Werner et al., 2008; Taylor, 2014). They are also a key component in evoking behavioural reaction (Sessler, 2008). Considering the exposure to the heat, physiological reaction such as the greater flow of blood through the skin (the dilation of blood vessels), stimulation of the sweat glands and an increase of evaporation heat loss were observed (Connolly and Worthley, 2000; Barnes et al., 2004). In turn, the impulses of cold cause, among others, cutaneous vasoconstriction which leads to a core-to-shell temperature gradient increase and thus a shell-to-ambient gradient minimalisation (Taylor et al., 2014).

Evoking behavioural thermoregulatory reactions is linked with conscious perception of temperature (involving the cerebral cortex). These changes of behaviour enable the animals to cope with too high or too low an ambient temperature (Refinetti and Horvath, 1989; Angrecka and Herbut, 2017; Herbut and Angrecka, 2018).

There are two terms pertaining to body temperature: internal temperature (body core temperature), which determines the thermal conditions prevailing in the regions of the abdominal cavity, rib cage and skull, and external temperature (shell) pertaining to the skin surface, subcutaneous tissue and muscles (Gagge et al., 1986). The thermoregulatory mechanisms permit maintaining a stable level of the body core, whereas the temperature of the shell shows major variability. It is considered that the skin temperature performs as a buffer between the inside of the body and the outside environment (Sokabe and Tominaga, 2009). Moreover, some organs are considered as heat sources as they are characterised by higher metabolic rate (brain, heart, liver, kidneys). Skin, adipose tissue and bones are less active. They can play a role as short-term heat sinks during a phase of altered heat storage. During exercising, an elevation of skeletal muscle metabolism occurs and thus a higher level of heat production is activated (Taylor et al., 2014). Taking into consideration large tissue muscle mass, the production of heat via the contraction of skeletal muscles is an excellent, evolutionary protection of the body against excessive cooling (Hohtola, 2004). Table 1 summarises some studies` results regarding temperature values of

cattle's body sites that were established under close-to-neutral and neutral ambient conditions.

The environmental conditions in farms are the most important factors affecting an animal's thermoregulation. Although the air temperature and relative humidity may be key in determining the exchange of heat between the animal and its surroundings, other relevant microclimate factors such as air movement and sunlight also play a significant role in levels of heat stress (Buffington et al., 1981; Shioya et al., 1997; Herbut et al., 2018). Changes in air velocity influence the convection cooling of cattle which - in combination with solar radiation - has a very significant impact on the regulation of thermal balance of cows (Davis and Mader, 2003; Herbut et al., 2013).

Different technological solutions may be used to alleviate thermal stress in farm animals. An evaluation of the implementation of these technologies' effectiveness may be based on the reliable monitoring of physiological parameters such as an animal's peripheral and core temperatures. Except for the changes in thermal balance caused by untypical environmental factors, some of the physiological conditions such as oestrus, the stage of pregnancy, birth, or the digestion of food can also affect the fluctuations in body temperature (Lefcourt and Adams, 1998). These changes can be determined with increasingly reliable measuring instruments. In this case, also important are the early detections of increased animal body temperature associated with bacterial or virus infections. As Lee et al. (2016) have stated, body heat monitoring may be very useful for preventing massive economic damage from pandemics affecting domestic animals.

3. Peripheral temperature measurement in cattle

Bearing in mind different local metabolism, variability of blood flow, tissue conduction and unceasing thermal energy redistribution, it is obvious that individual areas of the body are characterised by different temperatures (Taylor et al., 2014). Sellier et al. (2014) conducted a reliable literature review about the methods to precisely measure the animal body. The authors defined three zones of the body from which temperature may be taken: body core temperature, mid-peripheral temperature and peripheral or surface temperature. Table 2 presents some studies that investigated different techniques for measuring peripheral and mid peripheral temperature in cattle.

Nowadays, technologically advanced infrared cameras can be applied both in human and animal studies. These devices enable taking a single picture as well as videos of the temperature distribution and/or it fluctuations on the body surface. Noninvasive, non-contact equipment is especially useful in measurement-taking in large animals (Godyń et al., 2013). It was proven that some areas of the body have a different thermal emission (Fig. 1). The eye, udder or base of the ear, are characterised by higher temperatures than other body locations (Poikalainen et al., 2012; Hoffmann et al., 2013; Soerensen and Pedersen, 2015). Skin areas less isolated with a good blood perfusion - and thus higher infrared emission - may be called 'thermal windows' (Klir and Heath, 1992). These body areas are not so affected by ambient temperature as other body regions (Soerensen and Pedersen, 2015).

Poikalainen et al. (2012) used a thermal imaging scanner to evaluate the radiation of some body regions in cows, kept at an air temperature of 9 °C. The authors analysed the body surface temperature of the left side of the animal's body. The average temperature of this large body region was 23.9 °C. The highest temperatures were found in the eye and udder area (Table 1). In the study of Hoffmann et al. (2013) the results of using an infrared video camera for recording the temperature of cows showed that the eye had a higher temperature compared to the skin temperature of the shoulder (36.98 °C vs 34.91 °C). The mean skin surface temperature of the back of the ear was 35.60 °C. The authors also measured the vulvar temperature using a vaginal logger. The mean value of this parameter was 37.22 °C. George et al. (2014) evaluated the relationship of rectal, vaginal, infrared eye and muzzle temperature in cows and sheep. Deep body temperature (rectal and vaginal) was

Table 1
Literature references regarding surface and internal body temperature values in cattle kept under neutral and close-to neutral-thermal conditions.

	Body site	Mean temperature values (°C)	Comments	References
Surface temperature	eye	28.6	Lactating cows.	Poikalainen et al. (2012)
	udder	30.7		
	flank	27.9		
	muzzle	27.7	The air mean temperature of the experimental area was 9 °C.	
	left foreleg (regio ungulae)	18.2		
	right foreleg (regio ungulae)	22.5		
	left hind leg (regio ungulae)	17.2		
	eye	33.5	Dairy heifers (not pregnant and not lactating).	Salles et al. (2016)
	eye area	36.8		
	forehead	28.4	The mean ambient temperature during the study was 22.5 °C.	
	left foreleg	30.4		
	flank	30.1		
Internal temperature	ear canal	38.4	Feedlot cattle. The data were established when the hourly ambient temperature averaged 2.0°C.	Mader et al. (2005)
	rectum	38.77[1] 39.54[2]	[1]Lactating cows. The mean ambient temperature during the study was 17.2 °C.	Suthar et al. (2013)
	vagina	38.78[1] 39.48[2]	[2]Early post-partum cows. The mean ambient temperature during the study was 12.6 °C.	

measured using veterinary thermometers. Taking into consideration the results of the study on cows, the mean values obtained were 38.9 °C, 38.7 °C, 37.1 °C and 32.4 °C, respectively. The results showed a high correlation between rectal and vaginal temperatures and a moderate correlation between core (both sites) and eye temperature. Moderate association was also found between eye and muzzle temperature and a lack of correlation between body core and muzzle temperature. In the sheep the results were different. The authors suggested that the explanation of this fact may be associated with the number of experimental animals (there were more sheep than cows). Moreover, the cattle before measurement had a natural tendency to lick their muzzle; this was not observed in the sheep.

In the study of Salles et al. (2016) the temperature of both sides (left and right) of some body areas was measured. In addition, the temperature humidity index (THI) was calculated and the respiratory rate, and

rectal temperature and heart rate were evaluated. The highest mean temperature values were found in the eye area and the lowest in the forehead (Table 1). Similar temperature values (around 30 °C) were found in the left foreleg and in flank. These authors found a high correlations between THI and the right flank, left flank and forehead temperatures. Moreover, the temperature of the forehead was highly associated with rectal temperature. In study of Daltro et al. (2017) different genetic cattle groups were subjected to thermal stress. The cattle were exposed to high ambient temperatures during the day (a non-shaded location). The thermograms were taken from the right and left area of the animal, eye, lateral and posteriori region of the udder, and the right forelimb area in the posteriori foot was also taken into consideration. Additionally, respiratory frequency, rectal temperature, cardiac frequency, black globe humidity index (BGHI) and heat tolerance index were analysed. One of the study's results was the finding that

Table 2
Publications references of measurements of peripheral and mid peripheral temperature in cattle.

| Animal	Body site	Device/technic	Reference
Holstein Friesian lactating cows	four different areas between the groove of the udder and the hind leg and median suspensory ligament on caudal udder skin surface	Infrared camera ThermaCam E2 FLIR Systems (FLIR Systems Inc., Wilsonville, USA).	Pezeshki et al. (2011)
Lactating cows	udder, eye, flank, muzzle, left and right forelegs, left hind leg	Thermal imaging scanner Fluke TiS (Fluke, Everett, Washington, USA).	Poikalainen et al. (2012)
Herford x Angus calves	eye and one centimetre surrounding of its area	Infrared camera FLIR S60 (FLIR Comp., Boston, MA).	Schaefer et al. (2012)
Holstein Friesian, Jersey and hybrids cows	eye, back of the ear, shoulder	Infrared video camera OPTRIS® PI 160 (Optris, Berlin, Germany).	Hoffmann et al. (2013)
Senepol pregnant cows	eye, muzzle	Infrared camera FLIR Therma CAM P65HS (FLIR Systems AB, Danderyd, Sweden).	George et al. (2014)
Holstein cows and Angus feedlot cattle	lacrimal caruncle region of the eye	Infrared cameras FLIR I40 and E60 (FLIR Systems Inc., Wilsonville, USA).	Church et al. (2014)
Holstein steers	three different sites around neck area; upper scapula, lower scapula, lateral neck	Button-shaped digital thermo-loggers (iButton DS1922L, Maxim Integrated, San Jose, CA, USA).	Lee et al. (2015)
Jersey heifers	left and right eye area, right and left eye, caudal left foreleg, cranial left foreleg, right and left flank and the centre region of the forehead	Fluke Ti20TM thermal imager (Fluke, Everett, Washington, USA).	Salles et al. (2016)
Holstein Friesian lactating cows	eye area and udders` quarters	Infrared camera FLIR i5 (FLIR Systems Inc., Wilsonville, USA).	Sathiyabarathi et al. (2016)
Holstein, ½,Holstein × ½ Girolando ¾ Holstein × ¼ Girolando	right and left area of the animal, eye, lateral and posterior region of the udder, and right forelimb region in posterior foot	Infrared camera FLIR T300 (FLIR Systems Inc., Wilsonville, USA).	Daltro et al. (2017)
Simmental cows	metatarsus of the hind leg	Novel automatic measurement system for cattle's surface temperature based on thermistor sensor.	Kou et al. (2017)
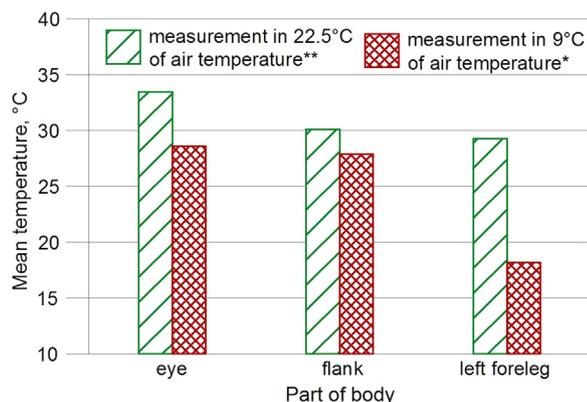
Fig. 1. Mean temperature of cow' body parts in different air temperature. (*Poikalainen et al., 2012; **Salles et al., 2016).

the purebred Holstein cows are more sensitive to ambient heat than crossbred cattle (Holstein x Girolando). In addition, positive correlations between surface temperature of the eye and udder with other studied physiological parameters were found. Moreover, the values of BGHI were also correlated with infrared temperature of the eye, left body area and post udder region. Heat tolerance index (calculated using respiratory frequency and rectal temperature) was highly correlated with the eye surface temperature and udder (both areas). The authors noted that the udder is a good area for determining the animal's thermal comfort.

The temperature of the udder was analysed in many studies concerning mastitis detection (Scott et al., 2000; Berry et al., 2003; Hovinen et al., 2008; Pezeshki et al., 2011). Some of these studies were conducted using an experimental infection of individual quarters with pathogenic bacteria. However, Sathiyabarathi et al. (2016) carried out their study on apparently healthy cows. Daily monitoring of udder infrared temperature was provided to detect naturally occurring mastitis. Also, daily somatic cell count tests and an electrical conductivity test was performed. The results showed significant differences between the temperature of the udder in healthy and mastitis-affected quarters. The subclinical mastitis was characterised with a mean udder temperature of ca. 38.0 °C, while the clinical mastitis quarter; 38.2 °C. The mean udder skin surface temperature of the non-mastitis quarter was 37.2 °C.

In addition to infrared thermography or infrared thermometers, there are data loggers or transmitters which can be attached to the animal's skin or implemented subcutaneously (McCafferty et al., 2015). Data loggers enable the storing of temperature data, in a certain time and within a user-defined interval. Usually this type of device contains a thermistor, a real-time clock, and an internal memory. It can be attached to the skin using glue, plaster or another type of fastening material. After some period of time the data of the device are downloaded. Another possibility to monitor the animal's temperature is the application of implanted data loggers. However, the subcutaneous implementation procedure requires surgical actions (McCafferty et al., 2015).

Currently, telemetry is a phenomenon used in many areas of life. It is not surprising, therefore, that many scientists have used this method to obtain a significant amount of data also in livestock studies (Hamrita and Paulishen, 2011). In brief, telemetry is the transmission of measurement data at a distance. The system for temperature measurement is based primarily on 3 factors - it is a measuring element (sensor) with a signal transducer and transmitter, a receiver/decoder and a data acquisition unit. The temperature sensor and transmitter are usually combined into one unit that is placed in / on the body of the animal. The transducer detects a physiological variable and transforms it into a form that can modulate the signal from the transmitter. The main role of the receiver is to decode or demodulate the signal. The data collection system converts the received signal into temperature values. It is

usually connected to a computer and the control of measurements and the ability to store data are attained through appropriate software. Remote data transmission in this technology is realised through, among other things; radio channels, the Internet or cellular networks (Güler and Übeyli, 2002; Hamrita and Paulishen, 2011).

An example of such measurements can be the study of Kou et al. (2017). The authors developed a novel automated monitoring technology of surface temperature in cattle. The researchers focused on skin surface temperature of the metatarsus of the hind leg. A special data detection device included a thermistor sensor and housing which was easily attached to the animal's leg. This equipment enabled the continuous monitoring of skin surface temperature over 3 days during winter, autumn and summer. The results showed that the measurements performed by the experimental device were comparable to those obtained by use of a commercially available thermometer. In winter time, the mean surface temperature was within the range of about 34.1 − 34.3 °C, it was similar in autumn (34.2 − 34.4 °C), while in the summertime it was 35.2 − 35.8 °C.

In another study, Schaefer et al. (2012) tested the possibility of using infrared thermographic measurements of the eye region, for automated detection of bovine respiratory disease (BRD). The authors monitored the temperature of the eye region of calves using a specially-designed station based on telemetry technology. Through this solution, infrared scanning was interfaced to a control system and every time a calf was drinking water the thermogram of its eye area was taken and collected. Taking the maximum eye temperature into consideration, the authors confirmed the effectiveness of this method in calves at risk of BRD. The automated infrared scanning enabled the identification of true positive and true negative animals. The true positive calves were characterised by higher peak temperature values (35.7 °C) compared to individuals from the other experimental group (34.9 °C).

A more invasive procedure was used in the study of Lee et al. (2016). The authors monitored the temperature in 7 Holstein steers by using subcutaneously implanted thermo-loggers. The devices were implemented in three places on the animal's neck (a 2 − 3 cm long skin incision) and the readings were taken after four and six months. The analyses revealed the existence of characteristic fluctuations of temperatures over 24 h, with rather stable temperature readings (37.10 − 37.36 °C). As the authors emphasised, the results of the experiment proved the usability of the applied devices in measuring the temperature of the surface layers of the body, and especially the location of the thermo-loggers in the upper scapula region seems to be provide the most accuracy. According to authors, however, the better potential of fever detection in cows using this method may be achieved with the development of a correction algorithm. These calculations could limit the influences of ambient temperature and animal resting behaviour.

The aforementioned methods for measuring of peripheral temperature in cattle can be prone to numerous errors or characterised with some limitation. In the case of telemetry interference in data transmission may occur and thus the signal of the sensor placed in /on the animal's body must be often reinforced by an antenna, and it often may need external power supplies (Ipema et al., 2008; Sellier et al., 2014). Data loggers implemented subcutaneously require for data recovery another invasive procedures (McCafferty et al., 2015).

Regarding the use of infrared thermography in animal studies, Church et al. (2014) identified different factors that may influence and disturb the measurements. During the monitoring of skin surface temperature, the emissivity of cattle skin, solar loading, wind speed as well as the distance between the camera and the measured object must be managed correctly to ensure accurate readings. These authors proved that eye infrared temperature differed, regardless of whether the cow's head was shaded or not. When the cows' heads were exposed to sunlight, the left eyes had a higher temperature than the right (38.8 °C vs. 38.2 °C, respectively). When the cows' heads were shaded, the temperatures of both eyes were similar. During the exposure of the cows'

Table 3
Publications references of measurements of body core temperature in cattle.

Animal	Body site	Device/technic	Reference
Crossbreed heifers	vagina	Radio transmitter (Wildlife Materials Inc., Carbondale, IL, USA). The device was placed in a flexible plastic anchors (US Patent Number 784,210).	Bergen and Kennedy (2000)
	ear canal	Data loggers (Mini-Logger Series 2000; Mini Mitter Inc., Sunriver, OR, USA). Thermistors (Steri-Probe skin surface temperature probe; Cincinnatti Sub-Zero Products Inc., Cincinnati, OH, USA).	
Charolais steers	rumen	Rumen boluses Cow Temp (Innotek Inc., Garrett, IN, USA).	Prendiville et al. (2002)
	ear canal	Data logger (Teagasc and Silsoe Research Institute, U.K.).	
	rectum	Digital thermometers (Jorgen Kruuse A/S. Model VT-801BWC Lot No 0701).	
Angus, Angus x Charolais, British x Continental steers	ear canal	Data logger (Stowaway XTI, Onset Computer Corporation, Pocasset, MA, USA).	Davis et al. (2003a)
Angus steers	rectum	Rectal probe (YSI Incorporated, Yellow Springs, OH) which was electronically logged using a data logger (XR440, Pace Scientific, Inc., Mooresville, NC, USA).	Davis et al. (2003b)
	ear canal	Data logger (Stowaway XTI108C + 36 + 46 logger with TMC2-1T external thermistor probes; Onset Computer Corporation, Pocasset, MA, USA). Transmitter (Implanted CorTemp™ telemetry transmitters, HQI, Palmetto, FL, USA).	
Pregnant cows	vagina	Data logger (Model HOBO Water Temp Pro, Onset Computer Corporation, Pocasset, MA, USA).	Hillman et al. (2009)
	rectum	Digital thermometer (Model GLA M525/550, GLA Agricultural Products, San Luis Obispo, CA, USA).	
Angus crossbred steers	ear canal	Data logger and thermistor (Stowaway XTI, Onset Corporation, Pocasset, MA, USA).	Mader et al. (2010)
Holstein cows	vagina	Microprocessor controlled temperature logger (Minilog 8, Vemco Ltd., Halifax, Canada) attached to a modified vaginal controlled internal drug release insert.	Vickers et al. (2010)
	rectum	Digital thermometer (GLA M750, GLA Agricultural Electronics, San Luis Obispo, CA, USA or KD 2110, SES Scala Electronics, Stahnsdorf, Germany).	
Angus steers	rectum	Self-contained indwelling rectal temperature monitoring device made up of; tail harness, probe container, the probe; TidbiT v2 temperature logger (Part UTBI-001, Onset Corp., Pocasset, MA, USA).	Reuter et al. (2010)
Brahman heifers	vagina	Temperature sensor Star-Oddi DST micro-T (Meter Mall USA, Marysville, OH, USA) attached to a progesterone-free modified vaginal controlled internal drug release (Pfizer Animal Health, Berlin, Germany; CIDR).	Burdick et al. (2012)
	rectum	The device elaborated by Reuter et al. (2010) was used.	
Lactating and early post-partum cows	vagina	Microprocessor controlled temperature loggers (Minilog 8, Vemco Ltd., Halifax, Canada) attached to a progesterone-free modified vaginal controlled internal drug release (Pfizer Animal Health, Berlin, Germany; CIDR).	Suthar et al. (2013)
Angus cows	rumen	Rumen boluses (Smart StockLLC, Pawnee, OK, USA).	Boehmer et al. (2015)
	rectum	Digital thermometer (Agricultural Electronics, Montclair, CA, USA; model #M216).	
Bulgarian Murrah buffaloes	ear canal	Tympanic Infrared thermometer (ThermoPet™, Sanomedics, Miami, FL, USA).	Ybañez et al. (2015)
	rectum	Digital and mercury-in-glass thermometers.	
Japanese Black non lactating cows	vagina	Data logger (Thermoclone type SL, NS Laboratories, Osaka, Japan) attached to a CIDR containing no progesterone (blank-CIDR, Zoetis Japan, Tokyo, Japan).	Sakatani et al. (2016)
Holstein lactating cows	vagina	Data logger (Thermochron iButton, Lawrenceburg, KY, USA) coupled to an intravaginal progesterone implant (Eazi-Breed, Zoetis, São Paulo, Brazil).	Polsky et al. (2017)
Angus, Charolais, and Brahman steers	rumen	Rumen boluses (Smartstock, Pawnee, OK, USA).	Lees et al. (2018)
	rectum	Digital thermometer (BD™, Becton, Dickinson and Company, USA).	

heads to a wind speed of 12 km/h, the mean eye temperature was 37.5 °C, while during a period of no wind it was 38.2 °C.

In medicine, methodological recommendations and measuring standards regarding thermography applications have been elaborated (Ring et al., 2010). Similar standards providing the opportunity to compare research results and evaluate their correct interpretation should also be developed for utilisation of such a method in animals.

4. Body core temperature measurement in cattle

The internal temperature of the body is similar to the temperature of the main organs such as the brain, heart and viscera (Sellier et al., 2014). In cattle, the common locations of taking these measurements are the rectum, ear canal, rumen and vagina. Table 3 presents some studies using different technics for measuring cattle's body core temperature.

The temperature of the rectum canal is the most popular method for evaluating health status both in humans and animals. The rectum is a hot place because of its thermal inertia, caused by a low perfusion and low level of heat exchange (Durotoye and Grayson, 1971). Reducing heat removal because of well-insulation is also a main reason why the gastrointestinal tract, auditory canal and vagina have a high temperature and are characterised by thermal gradients (Taylor et al., 2014). Moreover, measuring the heat radiation from the auditory canal also

seems to be a reliable equivalent of internal temperature, because the blood flowing through the vessels of the tympanic membrane comes from the branch of the carotid artery that also supplies the hypothalamus (Bergen and Kennedy, 2000; Chue et al., 2012). The optimum rectal temperature in cows is between 38.0 and 39.2 °C (Ammer et al., 2016). According to Yokoyama and Johnson (1993), the rumen temperature is within the range of 38 – 42 °C.

The relationship between three body locations –the ear canal, lumen of the rectum and the rumen - was established by Prendiville et al. (2002). The authors conducted their research over 5 days using different technologies: a telemetric system (a thermal probe was placed in the ear canal), the rectal temperature was measured traditionally but the values were taken every hour, and the rumen temperature was obtained by placing a bolus containing a thermal probe in the cow's stomach (Figs. 2 and 3). The authors found no statistically significant differences between the values of tympanic (38.2 °C) and rectal temperatures (38.4 °C); in turn, the temperature measured in the rumen was characterised by the highest values (39.0 °C).

Bewley et al. (2008) claim that due to the rumen microorganisms' activity, the temperature of this region is 0.5 °C higher than the body core temperature. In this study the authors found that reticular temperature and rectal temperature were strongly correlated. The mean of the reticular temperature was 39.28 °C, while the rectal was 38.83 °C. Some study results also indicate that there is a high correlation between
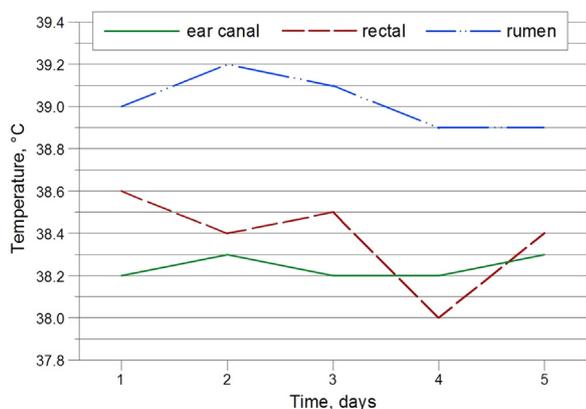
Fig. 2. Daily average body core temperature measured in different sites during 5 days.
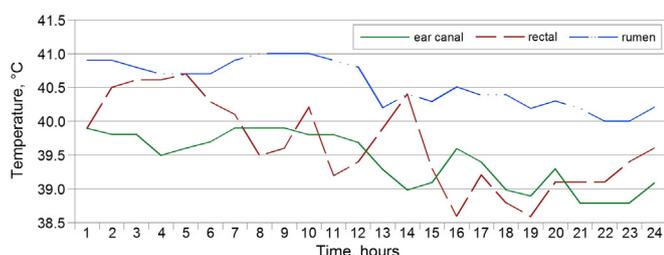measurement period (Prendiville et al., 2002).

Fig. 3. Changeability of hourly body core temperature measured in different sites (Prendiville et al., 2002).

rectal and vaginal temperature (Vickers et al., 2010; Sellier et al., 2014). Suthar et al. (2013) used technically identical temperature loggers to monitor rectal and vaginal temperature in 11 postpartum (135 days in milk) and 12 early post-partum (3 days in milk) dairy cows. The authors found a high association between these parameters in both groups of cows (Table 1).

Burdick et al. (2012) pointed out that vaginal temperature may be a better indicator of changes in body core temperature in comparison to rectum as it has a greater blood flow. Bergen and Kennedy (2000) found a moderate association between vaginal and tympanic temperature. Portable data loggers and vaginal temperature radio transmitters were used in their study to continuously monitor heat in these body sites. Mean vaginal temperature in this study was 38.66 °C, while tympanic was 38.60 °C. The authors noted the difficulties related to continuous tympanic temperature measurements because of possible dislocation of the thermistor, as well as the potential for infection. A moderate correlation was found also between tympanic and rectal temperature in cattle (Ybañez et al., 2015). The authors took measurements in the morning and in the afternoon using infrared tympanic, digital and mercury-in-glass thermometers. Taking into account the warmer and colder period of the year, the authors obtained a mean rectal temperature at the level of 37.4–37.7 °C and tympanic at the level of 39.9 °C (morning warm season); in the afternoon it was 37.6–37.9 °C and 40.0 °C, respectively. In the colder period, the rectal temperatures measured in the morning were 37.0–37.3 °C and the tympanic temperature was 39.0 °C, in the afternoon it was 37.6–37.9 °C and 40.0 °C, respectively.

Another study using tympanic membrane temperature was performed by Davis et al. (2003a). These authors studied the effect of diet and a cooling system (sprinklers) on the thermoregulatory capacity of steers encountering hot periods. The studies were performed with data-loggers placed in the ear. On the basis of the recorded tympanic temperatures, it was found that the change of feeding time (shifted from the morning to afternoon hours), as well as the applying of sprinklers, were

effective in preventing the results of heat stress. The same method of measurement was used in the study of Mader et al. (2005). The authors monitored tympanic temperature of feedlot cattle in winter and in summer. The main aim of this study was to evaluate the impact of moving cattle over various distances on their body core temperature. One of the research's results showed that moving cattle affects an increase of tympanic temperature of 0.3–0.8 °C. In another study Mader et al. (2010) evaluated the tympanic temperature to study the effect of $KHCO_3$ and NaCl supplements to cattle fodder during hot weather. The analysis of the data did not prove any effect of the supplements on the lowering of body temperature. Nevertheless, when comparing the fluctuations in tympanic temperature recorded during days and nights, the authors indicated the presence of statistically significant differences between individuals more and less vulnerable to heat stress. The cattle with hyperthermia found during the day also demonstrated high values of the tympanic membrane during the night. In the individuals with better thermoregulatory capabilities, the lowering of the internal temperature was measured in the cooler part of the 24 h period.

Numerous studies were conducted using an intra-ruminal telemetric sensing device (rumen boluses) to monitor body core temperature in cattle (Ipema et al., 2008; Bewley et al., 2008; Al Zahal et al., 2009; Boehmer et al., 2015; Lees et al., 2018). As it was mentioned previously, there are some limitations in using this technology. Regarding the application of an intra-ruminal telemetric sensing device there may occur some interference in data transmission caused by distance to the animal or its lying position (Ipema et al., 2008). Moreover, as Bewley et al. (2008) found, drinking cold water may cause a drop of rumen temperature even by 8.5 °C.

Al Zahal et al. (2014) confirmed the effectiveness of continuous temperature measurements by using the bolus containing the device transferring temperature data in early detection of febrile conditions, as well as the changes in temperature associated with the course of subclinical acidosis. The experiment involved four groups of animals fed a different energy dose. In addition, some animals were subjected to experimental infection of the udder quarter with the endotoxin from Escherichia coli. In the study, changes in vaginal temperature were also obtained from temperature data-loggers. After administering the injections with the endotoxin, a significant increase of the vaginal temperature was observed. The increased temperature was also noted in the rumen. Nevertheless, when compared with the vaginal temperature, the values recorded in the forestomach were lower by ca. 0.5 °C. The rumen bolus was useful in determining the effect of diet on the rumen temperature, but only until the time of the endotoxin injection. The inflammatory condition of the udder contributed to the reduced food intake, therefore the differences in the rumen content temperature between the individuals of particular groups were not that evident.

Boehmer et al. (2015) evaluated the effectiveness of ruminal temperature compared to rectal temperature measurements and the influence of ambient temperature. One of the study's results showed that as the ambient temperatures rise (above 34 °C) there is a greater correlation between values of rumen and rectal temperature (40.2 and 40.8 °C, respectively).

In a more recent study, Lees et al. (2018) tested the effect of environmental heat on rumen temperature in three different breeds of steers (Table 3). The rumen boluses used in this experiment were an active radio-frequency identification transmitter (RFID). The equipment enabled the transmission of the rumen temperature at 10 min intervals over 130 days. In this study, the animals were either exposed to the sun or shaded. Regardless of the breeds and treatments, a similar temperature diurnal pattern was noticed- the lowest temperatures occurred in the morning and the maximum at about 4:00 p.m. Moreover, the mean rumen temperature (of all the studied steers) was at the level of 39.4 °C. The maximum temperature obtained through the study was 43.7 °C in an un-shaded Angus steer during a very hot weather period. The results showed that the unshaded Angus steers' rumen temperature measured at night was lower than in individuals of the same breed kept

in pens with shade structures. This may be explained by the heat exchange mechanism activation in heat stressed animals. During colder hours a greater thermal load (gained during the day) may be emitted to the surroundings (Brown-Brandl et al., 2005; Mader et al., 2010).

Other than rumen boluses, a search was conducted for devices which may remain in other body sites for a longer period of time. The special housing of temperature meters was designed (Reuter et al., 2010; Suthar et al., 2013; Hillman et al., 2009). Reuter et al. (2010) constructed a special device to measure temperature in the rectal cavity. This consisted of a metal harness with the probe attached to it; the harness was fastened to the tail of the animal. In this way, the authors obtained reliable, multi-hour measurement data. Another way of carrying out the measurement continuously is to use a data logger attached to modified vaginal controlled internal drug release inserts (CIDRs) (Suthar et al., 2013; Polsky et al., 2017).

Other than using vaginal temperature to compare it with the heat of other body sites, it may be used as an identificator in oestrus detection. Sakatani et al. (2016) evaluated the effectiveness of hormonal preparations used to trigger the oestrus. In the study the authors measured the vaginal temperature and walking activity in cows. They also performed a comparison of vaginal temperature values in oestrus and non-oestrus cows. Regardless of colder and hotter periods of the year, the oestrus cows had a higher vaginal temperature (from 38.7 to 38.8°C) compared to non-oestrus females (38.4 °C). Furthermore, this experiment demonstrated that the measurement of vaginal temperature is a better indicator of the readiness to reproduce than measuring the locomotive activity by means of pedometers. This was confirmed by Polsky et al.'s (2017) research, who measured vaginal temperature in synchronised cows to determine how the body temperature and environmental conditions affect oestrus activity. The mean vaginal temperature during the 3 day period before artificial insemination was 38.9 °C (max. 39.7 °C and min. 38.0 °C). The authors concluded that oestrus activity is higher when the THI is lower. Moreover, under high ambient conditions the cows characterised by a higher percentage of time with a vaginal temperature of ≥ 39.1 °C had a lower number of pregnancies per artificial insemination.

5. Conclusion

An analysis of the professional publications regarding measurements of peripheral and deep body temperature led to the conclusion that these methods have high research and diagnostic potential. Cattle experience diurnal changes in body temperature which nowadays may be captured by many types of increasingly more technologically advanced devices - infrared thermography, rumen boluses and thermistors inserted in the ear canal or intravaginally. This equipment often provides the continuous monitoring of health status and well-being of the cattle, which is extremely important when taking account also economic factors. A key issue is also carrying out this research without subjecting the animal to any discomfort. Unfortunately, some techniques involve invasive procedures such as tissue damage for placement of the devices, thus they are debatable from an animal welfare perspective. In addition, some measurements still need to be standardised to enable better and more comparable results, for example for different cattle species, breed, age, health and environmental conditions.

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Conflict of interest

There are no conflicts of interest.

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