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Inter-animal radiation as potential heat stressor in lying animals

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Abstract A model for predicting inter-animal radiant heat exchange in shaded animals is presented, with emphasis on mature cattle. When a cow's surface temperature is 35 °C, as is common in warmer climates, it loses ~510 Watt m^{-2} as radiant heat. Net radiant heat balance depends on radiation coming from bodies in the vicinity. In the 30 °C radiant temperature shaded environment typical of warm climates, net radiant loss from a lactating cow is ~60 Watt m^{-2}, i.e., 30 % of its ~173 Watt m^{-2} heat production. Cows rest for 8–14 h day^{-1}. The heat exchange of a lying cow differs from that of a standing one: the body center is low and 20–30 % of its surface contacts a surface of relatively low heat conductance. Lying reduces the impact of the surrounding shaded area on heat exchange but increases that of heat radiating from neighboring cows. When a cow rests adjacent to other cows, with 1.25 m between body centers when in stalls, it occupies about 140° of the horizontal plane of view. Heat emitted from the animal's surface reduces the net radiant heat loss of a resting cow by ~30 Watt m^{-2}. In contrast, the presence of cows at 5 and 10 m distance, e.g., cows resting on straw in loose yard housing, reduces the net radiant heat loss of the resting cow by 9 and 5 Watt m^{-2}, respectively. Radiant heat input increases with animal density, which is beneficial in cooler climates, but acts as a stressor in warm climates.

Keywords Lying cow · Radiant heat exchange · Shaded area effect · Between-cow distance

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Introduction

The performance in warm climates of animals valuable to man is impaired by the prevailing higher temperatures in addition to the effects of suboptimal nutrition. Deficient performance has led to a large body of research on the physiological effects of high temperatures, centered on mechanisms of heat loss and metabolic heat production in animal species. Loss of heat by conduction, convection and evaporation has been examined in detail in contrast to the exchange of heat by radiation (Collier et al. 2006). The radiant component of heat stress is additive to, and frequently independent of, air temperature, wind velocity and ambient humidity effects on the thermal balance of the animal. The present study examined the radiant heat emitted from the bodies of animals as an additional ambient heat stress source.

Direct solar radiation is by far the most important source of heat in sun-exposed animals, and can be three to four times that generated in their metabolism (Webster 1974). As a consequence, sheltering farm animals from direct solar radiation is required for higher productivity in warmer climates (Schütz et al. 2008). The shelters used in animal farming, however, vary greatly in their hemispherical radiation characteristics (Kelly et al. 1950). Most research on radiant heat stress in farm animals has addressed the environmental global radiant heat provided by different types of roof (Eigenberg et al. 2010). The global radiant heat load has served as a measure of radiant heat stress in thermal balance models of both animals and man (Valtorta et al. 1997; Keren and Olson 2006; Matzarakis et al. 2007). In shaded animal environments, the spherical radiant heat input consists predominantly of long-wave radiation (> 3 μm) for which absorptivity and emissivity are above 0.9 for most surfaces present in animal housing, as well as of a variable amount of diffuse and reflected solar beam radiation (Monteith and Unsworth 2007). The semi-natural environments created by shading animals vary in their geometrical characteristics and hence in the intensity and distribution of the long-wave radiation emitted by various radiation sources (Bond et al. 1967). Mean global radiation is therefore of limited assistance for targeting the relative importance of the various sources of radiation present in the shaded semi-natural environments. Identifying the relative impact of radiation sources present in these environments is however required to alleviate radiant heat stress by shade structure design. The reduction of radiant heat stress is specifically advantageous for the higher producing dairy cows in warmer conditions as these animals are particularly sensitive to elevated temperature and humidity and are kept predominantly in shaded environments (Berman 2005).

Determining the relative impact of radiation sources present in the shaded environment on the radiation balance of a standing animal became feasible with a novel model (Berman 2012). In that model, the relative representation of radiation sources on body surface was determined by geometrical relations. The thermal radiation balance was summed from radiant heat gained from surrounding radiation sources (including animals) and that lost from the animal surface. It estimated the contribution of shelter structure characteristics, climate components and animal's density on the radiant thermal balance of the animal standing in a loose housing shed. In the main, that study indicated a large potential for reducing the heat stress of heat on animals standing in the shade of a loose housing shed by designing shelters according to local sky radiation intensity. That study did not examine the radiant heat emitted by the body of shaded lying animal as an additional component of environmental heat stress.

The importance of conditions during lying is indicated by the time cows spend lying. Cows spend 8–14 h/day lying, with few clear-cut effects of milk yield, season or climate (Kendall et al. 2006; Gomez and Cook 2010; Steensels et al. 2012), or housing when conditions are not extreme (Fregonesi et al. 2007; Calamari and Bertoni 2009; Krawczel et al. 2012). The considerable time spent lying in the dairy cow justifies considering the effects of lying on radiant heat loss. In the lying cow, the smaller convective heat loss due to lower air velocity and smaller exposed surface increase markedly the sensitivity to ambient temperature (Berman 2005), which enhances the value of radiant heat loss. There are two main systems to accommodate the shaded lying cow in farming for higher producing cows. In the loose housing system, the cows are free to move; they feed and lie over a shaded surface and are free to choose the between-cow distance. In the free stalls housing system, lying is restricted to stalls, cows lie parallel to each other, the distance between cows is fixed and only a relatively small alley is available for free movement. It may be presumed that loose housing and free stalls housing do not differ in their air temperature and humidity. These two housing systems may however differ in the radiant heat loss of lying animals.

There is little or no information on the effects of lying on radiant heat loss. Neither did a search of literature reveal studies on the radiant heat exchange between recumbent bovines. The present study examined the radiant heat exchange between lying cows when the distance between them varies from that found in stall housing systems to the distances prevailing in loose housing systems. Tentative differences in radiant heat loss may reach critical importance in the higher producing dairy cattle in warmer climates.

Methods

General approach

Bodies exchange heat between their surfaces by thermal radiation according to the Stefan-Boltzmann law. The body surface of shaded bovines in warm climates lies within a narrow range, usually from 35 to 37 °C (Umphrey et al. 2001; Keren and Olson 2006; Berman 2008). At this temperature, the body surface emits about 519 Watt m^{-2} as thermal radiation according to the Stefan-Boltzmann law, independently of hair coat thickness or air temperature and velocity (Monteith and Unsworth 2007).

The thermal radiation balance of an animal depends on the relative body surfaces facing environmental components and their respective radiant temperatures. The portion of body surface facing a particular environmental component is expressed by the angle of view that contains the particular environment component as seen from the body center of the animal (Berman 2012).

Specific approach

The case of an animal in a shaded animal housing environment is similar to that of a man in the shade of a room. The approach needed for the solution of the radiant heat exchange of such an animal therefore is much simpler than that developed for the more complex urban outdoor environment. The complexity of the latter environment and its changes with seasons requires for its analysis a model comprising a much larger number of elements (Matzarakis et al. 2007). The approach here used differs from that adopted for a human room environment (Johnson and Watson 1985), in that it allows for variable view factors. The angle of view of environmental components as seen from the center of the animal body depends on body center height above ground. In a standing cow, body center is at 1.1 m above ground, while in a lying cow it is at about 0.35 m above ground (Brody 1945; McGovern and Bruce 2000). Moving from a standing posture to a recumbent one lowers body center and consequently changes the view of the environment by the recumbent cow (Fig. 1). The proportions of angles of view of the shading roof or the sky, i.e., the upper hemisphere of the shaded animal, are not much modified by recumbency. Recumbency modifies

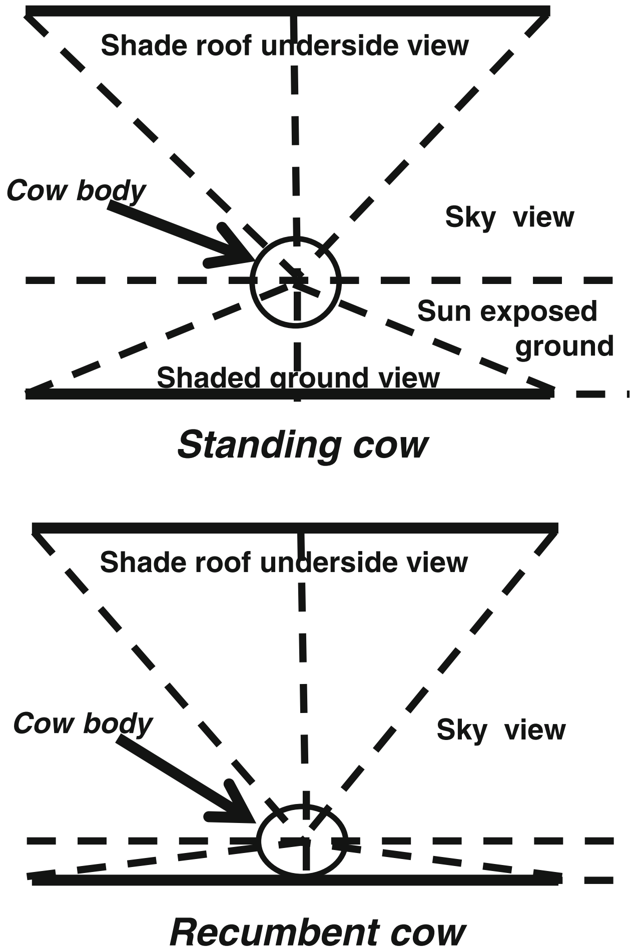

Fig. 1 Schematic representation of the main components of radiant shaded environment and of the angles of view of the components for a standing cow and for a recumbent cow

predominantly the proportions of the angles of view in the lower hemisphere: it reduces the portion of body surface viewing the sun-exposed ground, while the view of the shaded ground is increased. Recumbency also alters the portion of body surface viewing the neighboring cows, in particular when cows lie in proximity to each other, as in stalls.

Angle of view of shaded area

The angle of view of the shaded area depends on the body center height above ground as well as upon the size of the shaded area per cow (S) in the housing system. This study examined the effects of shaded area per cow and body center height on the angle of view of the lower hemisphere. A data set was created that consisted of two body center heights, 0.35 m or 1.1 m above ground representing the lying and the standing cow and, within each of body center height, a variable shaded area per cow (from 2 to 20 m^2 per cow in 1 m^2 steps). The angle of view of the shaded area was calculated for each data combination.

In the recumbent cow, 20%–30 % of body surface are in contact with the ground (Bruce 1977). This area does not exchange radiant heat with the surroundings. It represents about 25 % of the 360° body circumference, i.e., it is of about 90°. The effective angle of view of the shaded area surrounding the recumbent cow was therefore estimated by subtracting the angle of the area contacting with the ground, i.e., 90° from the two-sided angle of view of the shaded area predicted by the respective regression. The relation between the angle of view of the shaded area and the shaded area per cow (m^2 per cow) was calculated from these data by a second order polynomial regression of the log10 transformed data of the angle of view as the dependent variable, and the shaded area per cow (S) and its square (S^2) as the independent variables.

Angle of view of neighboring cow

The portion of body surface viewing a neighboring cow changes as a function of the distance between the two animals. The environment surrounding the body of a recumbent cow may be viewed in its vertical plane of view and in its horizontal plane of view. The vertical plane views the sagittal aspect of the neighboring cow and of surrounding environment components. The horizontal plane views the longitudinal aspect of the neighboring cow and of surrounding environment components. A partition of the environment into two planes requires the representation of the cow's body in a geometrically symmetrical form. A cylindrical representation of the cow's body has been adopted in studies of heat exchange (Clapperton et al. 1965; Wiersma and Nelson 1967; Webb et al. 1986). When the lying of cows is restricted to within typical 2.5 m long and 1.25 m wide stalls (Tucker et al. 2004), two lying cows may be visualised as two parallel cylinders. The side view of a 600 kg dairy cow may be represented by a 0.73 m diameter and 2.5 m long cylinder, with its center at 1.1 m above ground for a standing cow and at 0.35 m above ground for a lying cow (McGovern and Bruce 2000). The actual main body length measured for 600 kg cows, however, is about 1.5 m from pin bone to front of shoulder, with an additional 0.7 m from shoulder to muzzle when the neck is not bent (ASABE 1985). Assuming that the neck is bent for about half the time a cow is resting, these add up to an average 1.85 cm effective body length, which was preferred for calculating the angle of view in the horizontal plane. The discrepancy between stall dimensions and cow main body dimensions represents the free space in the stall within which a cow may locate itself.

Thermal radiation exchange

A lying cow exchanges thermal radiation with the surrounding surfaces: it emits thermal radiation from its surface according to its temperature and absorbs thermal radiation emitted from the surrounding surfaces according to their temperature. In this study, for an air temperature of 30 °C, the surface temperature of the cow (Ts) was presumed as 35 °C and shaded ground surface temperature (Tg) as 30 °C, respectively (Berman 2012). The thermal radiation emitted is proportional to the Stefan-Boltzmann constant (°K^4 × 5.67 × 10^{-8} Watt/m^2) multiplied by the emissivity coefficients (e). The thermal radiation absorbed is the incident thermal radiation multiplied by the absorptivity coefficient. The thermal radiation emissivity and absorptivity coefficients of the hair coat surface of the cow and of the shaded ground are ~0.95 (Monteith and Unsworth 2007). The thermal radiation net balance (Rbal, Watt/m^2) was calculated by:

$$\mathrm{Rbal} = \mathrm{A_r} * \left[(Ts+273)^4 - (Tg+273)^4\right] * 0.95 * 5.67 * 10^{-8}$$

Where: A_r is the angle of view relative to angle at 1.25 m distance between cow body centers.

Data analysis

In the vertical plane of view (Fig. 2), the angles of view of environment components can be determined by the sagittal section of the two cylinders simulating the bodies of the cows, with a 1.25 m distance (A) between their centers at a 0.35 m height (B) above ground and a diagonal (C) connecting the two. In the horizontal plane of view of the angles of view of x^2 environment components, a side view of a lying cow body is represented by a longitudinal section of such a cylinder, i.e., a 1.25 m wide (A) and 2.5 m long (B) rectangle (Fig. 3), within which a 0.73 m wide and 1.85 m long cow body locates itself. The angle of view delimiting the cow in the neighboring stall would represent the body of the neighboring cow as perceived from the center of the body of the reference animal. The angle of view was derived from the value b/c (the sine of the angle) multiplied by 57.295. Multiplying the value of this angle by 2 provides the full, two-sided angle that contains the body of the

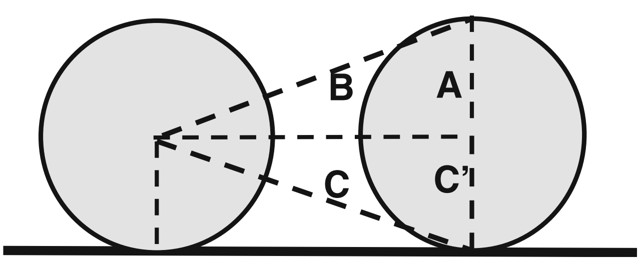

Fig. 2 Schematic representation of two cows lying in stalls as sagittal sections of two parallel cylinders, 0.73 m diameter, centers at 0.35 m above ground and at 1.25 m from each other. B Radius of cow body, A distance between cow bodies centers; the angle AC represents half the angle of view of the adjacent cow; the body surface contained within the angle of view is exposed to the radiation emitted by the surface of the adjacent cow

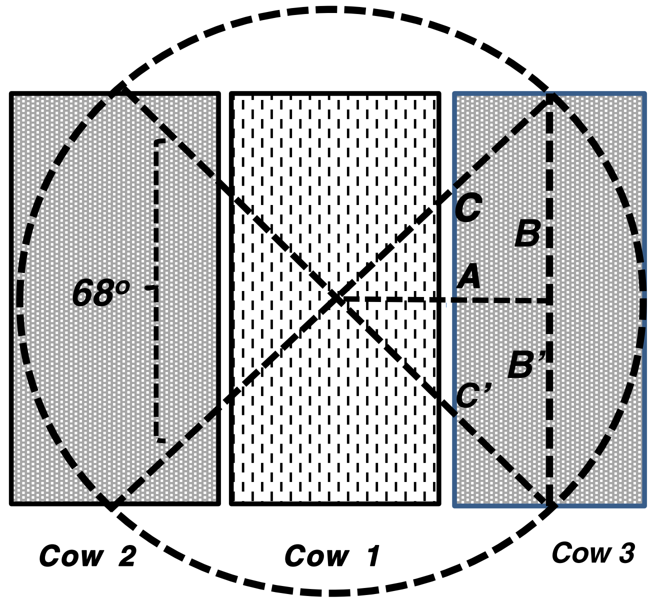

Fig. 3 Schematic representation of three cows' bodies lying in stalls as longitudinal sections of three parallel cylinders, 2.5 m long, 0.73 m diameter and at 1.25 m distance between cylinder centers. The circle depicts the angle of view (68°) of cows 2 and 3 as perceived from the center of the body of cow 1. A Distance between two body centers; B, B' radius of longitudinal section of cow body

neighboring cow as perceived by the reference animal body. This angle represents the portion of body surface that exchanges thermal radiation with the neighboring lying cow.

The effect of distance between cow bodies on the angle of view was assessed by calculating the angle of view with distance between body centers (D) of lying cows varied from 1 to 15 m in 0.5 m steps for the vertical and the horizontal planes of view. The effect of distance on the angle of view was estimated by linear regressions of the $\log_{10}$ transformed angle of view ($\log_{10}A_x$), as the dependent variable and $\log_{10}$ transformed distance ($\log_{10}D$) as the independent variable. The R^2 of the regressions were high, above 0.990, considerably higher than those obtained by 2nd order polynomial regressions of the data. The discrepancies between data calculated individually and data obtained by the $\log_{10}$ data regressions equations were very small, endowing the equations with a reliable predictive value. The $\log_{10}$ values of angles obtained by the regressions equations can be converted to degrees by calculating the $10^{\log\ \mathrm{angle}}$.

Results

Posture effect on shaded area view

Geometrical relations produce two effects of recumbency on the angles of view containing environment components that may be assessed qualitatively (Fig. 1). Increasing the shaded area per cow increases the angle of view that contains the shaded area, and thereby increases the portion of body surface exposed to a cooler shaded area. Reducing the height of body center above ground increases the angle of view that contains a given shaded area. Body center height is reduced when the animal is lying and is increased when the animal is standing. Moving to a recumbent posture changes the view of the environment as perceived by the lower body hemisphere, but only rather slightly that of the upper hemisphere. The small effect of posture on upper hemisphere perception is due to the small change in body center height relative to the 6–8 m mean shading roof height.

The lower body center in the recumbent cow reduces the mean portion of body surface viewing the shaded area from 108°±1.0 SEM in the standing animal to 23.8°±0.1 SEM in the lying animal—a very marked difference. The marked reduction in the body surface viewing the shaded area in the recumbent animal stems from the 20 % to 30 % of body surface, representing 90° of it, that are in contact with the ground and do not view the surroundings (Table 1). The lower portion of body surface viewing the shaded area is associated with a only a minor effect of size of shaded area per cow on the portion of body surface viewing it. This contrasts the situation in the standing animal, in which a relatively large exponential effect of shaded area per cow on the portion of body surface viewing it exists. The exponential relationship between the size of shaded area per cow and the angle of view of the shaded area in the standing animal was calculated by a polynomial logarithmic regression. Using other data transformations yielded greater discrepancies between predicted and calculated data, i.e., lower R^2 values and larger residuals. The R^2 value of this regression (0.998) was sufficiently high to provide an accurate prediction of the relation between shaded area size and the portion of body surface viewing it. The second order term was introduced to attenuate the effect of the linear term in order to reduce the discrepancies between the individually calculated values and the predicted values. The regression equation was:

$$A_{1.1} = 1.989 + 0.050 * log_{10}S - 0.064 * (log_{10}S)^2 \quad R^2 = 0.998$$

Table 1 Mean (±SEM) angle of view of the shaded area for a lying cow with body center height at 0.35 m and for a standing cow with body center height at 1.1 m. In the lying cow the portion of body surface in contact with ground (90°) was deducted from total body surface

Body center Height (m)	Mean (degrees)	SEM	Range (degrees)
0.35	23.8	0.14	21.9–24.3
1.10	108.1	1.09	94.3–112.0

Where: $A_{1.1}$ is the log10 of angle of view of shaded area (degrees) for 1.1 m body center height, and S is the shaded surface area per cow (m^2/cow).

View of neighbouring cows

In loose housing systems cows are free to choose their resting sites; they may lie close to each other to the extent that their bodies are in contact, or lie at variable distance of each other. In the free stall housing system, lying is restricted to stalls and moving takes place in the alley between the stalls. In cows lying in stalls, the 1.25 m width of the stalls is narrow enough to determine the orientation of cows and the distances between them. A cow lying in the proximity of another cow can be seen as obscuring the view of the environment in the vertical plane of view and in the horizontal plane of view.

Vertical plane of view

The effect of the presence of a neighboring cow on the vertical angle of view of a cow is represented here by analogy to sagittal sections of two cylinders of 0.35 m radius (B), lying side by side with their centers at variable distance (A) of each other (Fig. 2).

A cow lying next to another cow, as occurs in cows lying in stalls, is contained within an angle twice the size of the angle AC. The angle containing the neighboring recumbent cow decreases with increasing distance between cows (Fig. 4). The quantitative relationship between angle of view of the neighboring cow in the vertical plane (A_{vert}) and the distance between two recumbent cows (D) was calculated by an exponential regression:

$$A_{vert} = 1.596 - 0.968 * log_{10}D \quad R^2 = 0.9997$$

where: A_{vert} is the log10 of vertical angle of view of neighboring cow, and D is the distance (m) between body centers of neighboring cows.

The high R^2 value of this regression made it a good predictive tool of the relation between cow to cow distance and the angle of view of each other.

The angle of view that contains the body of a cow is 32° when the body center of a cow is at 1.25 m distance from the body center of the next cow, i.e., the distance between cow centers when lying in stalls, and declines to about 16° and <6° when the distances between cows are 2.5 or >7 m, respectively (Fig. 4). A cow resting in stalls faces two cows, one on each of her sides. Thus, in the vertical plane, 64° (i.e., 2×32°) of the surface of a cow are facing body surfaces of neighboring cows.

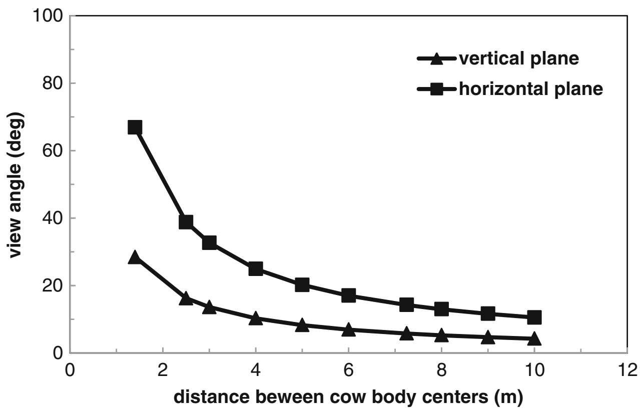

Fig. 4 Effect of distance between cow centers (*m*) on the angle of view (*degrees*) that contains the body of the adjacent cow, when seen in its vertical plane (sagittal section of the body) and its horizontal plane (longitudinal section of the body)

Horizontal plane of view

A lying cow may also be seen in a horizontal plane when the angle of view of the neighboring cow depends upon the distance between their body centers (Fig. 3). The angle of view that contains the maximal body length of the cow in the horizontal plane, as seen from the center of the reference cow body, declines exponentially with increasing distance between body centers (Fig. 4). The following exponential regression was calculated to describe the relation between the distance between body centers of cows and the angle of view (A_{hor}) containing the neighboring cow:

$$A_{horiz} = 1.9629 - 0.9404 * log_{10} D \quad R^2 = 0.9988$$

where: A_{horiz} is the log10 of horizontal angle of view of neighboring cow, and *D* the distance (m) between body centers of neighboring cows.

The horizontal plane angles of view values predicted by the equation for the 2.5–15 m distance between body centers departed from the individually calculated values by 1° at most. The angle predicted for the smallest between-body-centers distance, namely 1.25 m, was 74°, while that individually calculated was 68°. Using a polynomial expression only exacerbated the discrepancy. Such differences between calculated and predicted values are probably to be expected at the lower end of the measured range. The value adopted for the horizontal angle of view containing the body of a cow lying in the neighboring stall at a 1.25 m distance between their body centers therefore was 68° on each side of the reference cow. The value declines to 20° when the distance between two lying cows is 5 m, and to 10° when that distance is 10 m (Fig. 4). These angles of view represent the effect of distance between cow bodies on their representation on the body surface as a function of the distance between the bodies. These values have to be multiplied by 2 in order to represent the stalls situation in which cows are present on both sides of the reference cow. Therefore, for cows lying in stalls, 136° of the horizontal plane of view consists of body surface of neighbouring cows at 35 °C surface temperature. Such an angle of view represents almost 40 % of the horizontal plane of view of the body surface of the cow.

Thermal radiation exchange

The angle of view containing the body of the next cow on the surface of the reference cow receives thermal radiation from a 35 °C temperature surface. When the distance between the two animals increases, the angle of view containing the next cow diminishes and is replaced by the view of the cooler, e.g. 30 °C, shaded ground. The decrease in radiant heat gain from the neighboring cow with increasing distance between them is marked (Table 2). The radiant heat gain from the body of the neighboring cow diminishes from 31 Watt m^{-2} when the distance separating their body centers is 1.25 m to 17, 9, and 5 Watt m^{-2} when the separating distances increase to 2.5, 5 and 10 m, respectively.

Discussion

The thermal balance of animals takes place by exchange of heat according to gradients of radiation, temperature and humidity between the animal and its environment. The latter two heat sources are distributed uniformly in the environment, whereas radiant heat is distributed heterogeneously in both natural and semi-natural environments. A novel approach, based on geometrical relations, that allows estimation of the distribution of radiant heat in animal shelters was developed for targeting its sources and their subsequent attenuation by shelter design or other means. In the first stage, it was shown that radiant heat stress may be reduced significantly by

Table 2 Change in horizontal plane angle of view and in net radiant heat loss[a] (Watt m^{-2}) with distance between body centers of reference cow and neighboring cow, when shaded ground temperature is 30 °C and that of cow surface 35 °C[b]

Distance (m)	Angle (degrees)	Radiant heat gain (Watt m^{-2})
1.25	68	31
2.5	39	17
5	20	9
7.5	14	6
10	10	5

[a] Radiant heat exchange for one side of a cow viewing another cow. Value has to be multiplied by 2 when cows are present on both sides of reference cow

[b] Calculated by subtracting radiant heat received from surrounding ground from radiant heat emitted by the reference cow

modifying components of the shading structure according to the distribution of radiation in the environment (Berman 2012). The next step, novel in itself, turned to examine the radiant heat coming from the bodies of lying animals. In the main, the radiant heat exchange of the lying animal differs from the standing animal mostly in the radiation exchange within the lower hemisphere of their surroundings—the result of the body center lower position.

In the recumbent animal about 25 % of body surface contacts the ground, and therefore does not exchange radiation with the shaded area. Also, in the recumbent animal increasing the surrounding shaded area only has a very small effect on radiant heat loss, in contrast to the large effect on the shaded area angle of view it has in the standing animal. These factors add up to a reduction in the shaded area view in the recumbent animal to about 25 % of that in the standing animal.

A number of factors specific to this body state affect the thermal balance of cows. A previous study indicated a lower air velocity in the proximity of lying body surface and a smaller exposed surface, which lower the ambient temperature at which respiratory heat loss recruitment is required (Berman 2005). This effect of lying, however, is counterbalanced to some extent by the 18–24 % lower energy expenditure of the lying bovine (Vercoe 1973; Schrama et al. 1993). In the lying cow, the 0.2 to 0.3 of body surface in contact with the ground does not exchange radiant heat with its surroundings, neither does it lose heat by convection and evaporation to the surrounding air. The suggestion was made that heat from the body surface in contact with the ground is lost laterally rather than being stored in the underlying ground acting as a heat sink (Bruce 1977). This conclusion might, however, be caused by the low heat capacity of the floor on which the animal rested in that latter study, relative to that of floors on which animals rest in dairy farms (Graee 1971). In either case, the thermal resistance of materials used as lying grounds varies widely, and their consideration is significant in calculating thermal balance.

The present study indicates that, in the lying cow, the body surface viewing the surrounding cooler shaded area is reduced to <30 % that in the standing cow. Particularly significant is the fact that, in the lying cow, the shaded area per cow has little, if any, effect on the portion of body surface exposed to it. This reduces the possibility of enhancing dissipation of excess heat from the body of the lying cow by increasing the surface of the shaded area per cow, in contrast to the situation in the standing cow. These findings are novel and of particular importance for animal housing design in warm climates.

In the stalls housing system, in contrast to the straw yard loose housing system, cows can rest only in stalls, in which the distance between cows, and their orientation, are fixed. As the number of stalls does not exceed the number of cows, a cow would generally rest close to and in parallel to one or two cows. The stall housing system creates a fixed set of radiant heat exchange relations for lying cows. In cows lying in stalls, the two cows resting in stalls adjacent to another cow occupy an angle of view of about 136° on the body surface of the latter, i.e., about 40 % of the horizontal plane of view. In those 40 % of the horizontal plane, the view of the shaded ground is replaced by the view of another cow's body. The effect of such replacement on the radiant heat balance is determined by the temperatures of the two bodies. At an air temperature of 30 °C, the surface temperature of a high producing cow is about 35 °C and the surface temperature of the shaded ground in the shed is about 30 °C. These data imply that about 40 % of the shaded area viewed in horizontal plane is replaced by the view of another cow body, the temperature of which is higher by at least 5 °C than the radiant temperature of the surroundings. By the Stefan-Boltzmann constant, a 1 °C change in surface temperature equivalent to a 6.5 Watt m^{-2} change in long wave radiation flux. In this particular case, the replacement of a shaded area view by another cow's body view would be associated with a 30 Watt m^{-2} deterioration of radiant heat loss from the body of the cow. In the above-mentioned conditions the radiant heat loss of a cow would be about 60 Watt m^{-2} (Berman 2006), so that the potential radiant heat loss is reduced by about 50 %. The importance of radiant heat loss may be inferred from the fact that it represents about one-third of the 173 Watt m^{-2} total metabolic heat production of a cow secreting 35 kg milk per day (NRC 2001) and that it is largely independent of, and additive to, convective and evaporative heat loss.

The radiant heat gain from the body of another cow depends on the distance between the two. The greater the distance to the neighboring cow, the smaller will be its representation on the surface of the reference cow, i.e., the angle of view that contains it. When cows are lying in stalls, at a distance of about 1.25 m between body centers, the adjacent cows occupy about 140° of the horizontal plane of view, and this angle declines rapidly to 20° and 10° when between-cow distance increases to 5 and 10 m. The decline with distance in the angle of view containing a neighboring cow leads to a decline in the net radiant heat gain, from 31 to 9 and 5 Watt m^{-2}, depending on the distance between cows. This indicates that proximity between resting cows significantly impedes the dissipation of excess heat from their body by radiant heat and creates an additional demand for convective and evaporative heat loss. This new viewpoint on the heat loss of the resting animal is novel, and has important implications for housing design, particularly in warmer climates.

The mean distance between lying cows is determined largely by the space allocated per cow in the shaded area. The cows lie to rest for 8–14 h per day (Kendall et al. 2006; Gomez and Cook 2010; Steensels et al. 2012), during which lactating Holsteins producing about 30 kg/day eliminate about 25 % of total excretions (feces and urine), about 10 kg fluids (Aland et al. 2002). The space provided per cow should address animal comfort needs as well as prevent of environment pollution by excreta. Recommended shaded floor space per cow varies from 1.4–2.5 m^2 per cow (Hahn 1985) to 4.2–5.6 m^2 per cow (Buffington et al. 1983) in the US, to 6.7–13.5 m^2 in the UK (Fregonesi and Leaver 2002). The shaded area per cow in loose housing in Israel has been increased over the decades (Berman and Wofenson 1992) from the previous 8 m^2 per cow norm to the present standardly used range of 16–20 m^2 per cow. This increase in shaded area, in conjunction with use of forced ventilation, reduced animal heat stress as well as bedding material requirements, and improved summer fertility and milk production (Folman et al. 1979; Berman et al. 1985).

The effect of between-cow distance on radiant heat input is additive to the effect of between-cow distance on convective heat loss (Berman 2006). In the pig, higher animal density and allowing huddling reduced the metabolic response to lower ambient temperatures (Mount 1960; Holmes and Mount 1966). Similar effects may be expected for cattle, by analogy, owing to interspecies similarities in metabolic responses to cold. In cooler climates, the heat input from adjacent animals may serve to reduce the feed energy required for maintenance of thermal balance. In the warmer climates, the opposite is desirable.

The effect of animal density, expressed as the average distance between cows, was shown here for the radiant heat exchange of lying animals. It was previously shown that, in standing animals, the surface area/cow at which a cow would perceive only cow bodies and very little of cooler surfaces would range between 4.2 and 8.7 m^2/cow, depending on the whether they present side or front views to each other (Berman 2012). In warmer climates, a reduced radiant heat load as well as increased freedom for behavioral responses to air temperature and air velocity are attained by greater shaded surface per cow for both standing and resting animals, thus reducing the need for heat stress relief.

Conclusions

In resting animals, the portion of body surface viewing the surrounding shaded surface is reduced to 25 % that of a standing animal. Increasing shaded area per animal has little effect on the body surface facing it in the lying animal in contrast to the situation in the standing animal.

When animals are resting in the shade close to each other, as in stalls, a large part of their body surface faces the warms surface of the neighbouring animals, which leads to a marked increase in their radiant heat input. This input of radiant heat is additional to, and largely independent of, convective and evaporative heat loss. It creates an additional source of heat, which is of particular importance in warmer climates.

Increasing shaded area per animal increases the mean distance between animals and thereby reduces the contribution of radiant heat from animal body surfaces—particularly important in warmer climates. A greater radiant heat loss reduces the need for heat stress relief by convective and evaporative means. The opposite applies to cooler climates.

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