INTRODUCTION

The embryonic stage currently occupies a greater proportion of the entire life of the commercial broiler than ever before. Therefore, the embryo’s physiological responses to its incubational environment have an increased effect on subsequent posthatch performance and processing yield. A thorough and in-depth understanding of the potential influences of various external stimuli on embryonic life and the monitoring of those parameters for maximal productivity are of importance to the broiler industry (Bamelis et al., 2005). Among various external factors, incubation temperature is considered to be a major factor that influences embryo temperature (French, 1997), heat production (Janke et al., 2002), and development (Decuypere and Bruggeman, 2007). Incubation temperature also has a major influence on the hatchability and posthatch performance of chickens (Wilson, 1991). Lourens et al. (2005) noted specific relationships between broiler embryo temperature and subsequent hatchability and posthatch performance.

It has been reported that the optimal incubation temperature for chicken eggs is 37 to 38°C (Wilson, 1991; Decuypere and Bruggeman, 2007; De Smit et al., 2008). French (1997) suggested that embryonic temperature is a function of incubator temperature, heat...
exchange between the embryo and its external microenvironment, and the metabolic heat production of the growing avian embryo. French (1997) further suggested that because the avian embryo is largely poikilothermic during early incubation, its temperature is largely influenced by the incubator temperature, and that during the later stages of incubation, as the embryo produces larger amounts of metabolic heat, its temperature rises above the incubator temperature.

Previously, Lourens et al. (2005) and Joseph et al. (2006) used eggshell temperature as a means to estimate embryonic temperature. Lourens et al. (2005) also graphically reported variations in broiler eggshell temperatures between 1 and 18 d of incubation. However, Eren Ozcan et al. (2010) and Lourens et al. (2011) suggested limitations associated with the measurement of eggshell temperature for the estimation of embryonic temperature, given that eggshell temperature can be influenced by the thermal conductivity of the eggshell and the velocity of air flow around the egg. In other studies, internal egg content temperatures (Turner, 1990; Janke et al., 2004; Renema et al., 2006) were used as standard expressions of embryonic temperature. Janke et al. (2004) suggested that embryonic heat production and body temperature may be estimated based on internal egg temperature. Although these techniques allowed for the determination of an egg’s internal environmental temperature proximal to the embryo, they were limited in application because of their relative invasiveness to the growing embryo (Turner, 1990; Janke et al., 2004) and because of the potential for increased embryonic mortality (Janke et al., 2004).

Pulikanti et al. (2011a,b) suggested that transponders may be safely implanted into the air cells of incubating eggs for the determination of internal egg temperature. Pulikanti et al. (2011b) successfully recorded the internal (air cell; $T_{emb}$) and external microenvironment (water vial; $T_{ext}$) temperatures of embryonated Ross × Ross 308 broiler hatching eggs between 10.5 and 18.5 d of incubation. These researchers subsequently used the $T_{emb}$ and $T_{ext}$ values along with incubator RH and atmospheric pressure values for the calculation of the water vapor pressure gradient across the eggshell ($\Delta P_{H_2O}$; Torr), eggshell water vapor conductance ($G_{H_2O}$; mg of $H_2O$/d per Torr), and specific $G_{H_2O}$ ($g_{H_2O}$ adjusted to a 100 g set egg weight basis; mg of $H_2O$/d per Torr per 100 g). However, Pulikanti et al. (2011b) did not use implanted nonembryonated eggs as external temperature controls, and they did not determine the $G_{H_2O}$ constants ($K_{H_2O}$) of embryonated eggs. Moreover, they did not provide detailed comparative profiles of $T_{emb}$, $T_{ext}$, and incubator dry bulb ($T_{inc}$) and data logger ($T_{log}$) temperatures during the second half of incubation. Therefore, the current experiment was conducted using Ross × Ross 708 broiler hatching eggs to compare the mean values and semicardian variations of $T_{emb}$, $T_{ext}$, $T_{inc}$, and $T_{log}$ and the internal (air cell) temperatures of nonembryonated eggs ($T_{nem}$) between 10.5 and 18 d of incubation. Furthermore, calculations of $\Delta P_{H_2O}$, $G_{H_2O}$, and $g_{H_2O}$ values of embryonated and nonembryonated eggs, and $K_{H_2O}$ values of embryonated eggs were performed.

**MATERIALS AND METHODS**

**General**

In total, 720 broiler hatching eggs were collected from a young (30 wk of age) Ross × Ross 708 breeder flock. The eggs were held under standard storage conditions for 3 d before set. Eggs having malformed shells, or that were contaminated, misshapen, cracked, or not within ±10% of the mean weight of all eggs collected, were discarded from the experiment. On d 0 of incubation, eggs were randomly labeled and weighed to record their set egg weight. At least 60 eggs were set on each of 8 replicate tray levels of a Jamesway model 500 single stage incubator (Jamesway Incubator Company Inc., Cambridge, ON, Canada). The eggs were incubated for 18 d under standard commercial conditions at 37.5°C dry bulb and 28.8°C wet bulb temperatures.

On d 10.5 of incubation, the eggs were weighed and candled, and those containing slanted air cells were discarded. Subsequently, on each tray level, 4 embryonated eggs were randomly selected and the air cells of those eggs were implanted with a transponder (implantable programmable temperature transponder; I-PTT-300; Bio Medic Data Systems Inc., Seaford, DE) for the determination of $T_{emb}$. Transponders were implanted in the air cells of 2 nonembryonated eggs and these were positioned within 5 cm from each implanted egg on each tray level for the determination of $T_{nem}$. Furthermore, 2 sealed water-filled plastic vials (10-mL capacity), each containing a transponder, were positioned within 5 cm from each implanted embryonated and nonembryonated egg for the determination of $T_{ext}$ (Pulikanti et al., 2011b). The materials and procedures used for transponder implantation and temperature data recording in this experiment were similar to those described previously by Pulikanti et al. (2011a,b).

**Hatch Monitor**

On d 18.5 of incubation, each implanted embryonated egg was candled, and the eggs that contained live embryos were placed in individual hatching baskets and subsequently transferred to their corresponding tray levels in a Jamesway model 500 single stage hatcher unit (Jamesway Incubator Company Inc.). The eggs in the hatcher were maintained at approximately 36.1°C dry bulb and 27.6°C wet bulb temperatures and were individually monitored for hatch every 12 h through d 21.5 of incubation.

**Embryo Survivability**

Survivability of the embryos was determined by candling eggs on d 18.5 of incubation and was further con-
firmed based on hatch success through d 21.5 of incubation (Pulikanti et al., 2011b). All of the egg parameters for embryonated eggs described below were determined on implanted eggs that contained live embryos through hatch (d 21.5 of incubation).

### Data Collection

Between 0 and 18 d of incubation, Tinc, incubator wet bulb temperature readings, and atmospheric pressure values were recorded every 12 h. Moreover, between 0 and 18 d of incubation, Tlog readings were recorded every 5 min using wireless data loggers (La Crosse Technology, La Crescent, MN). Furthermore, between 10.5 and 18 d of incubation, temperature readings were recorded every 12 h from transponders contained within water vials, nonembryonated eggs, and embryonated eggs for the determination of Text, Tnem, and Temb, respectively. Between 10.5 and 18 d of incubation, a total of approximately 16 Tinc (sixteen 12-h periods); 6,912 Tlog (sixteen 12-h periods × 12 h × twelve 5-min readings per h × 3 data loggers); 256 Text and Tnem (16 twelve-h periods × 16 water vials or nonembryonated eggs); and 416 (sixteen 12-h periods × 26 embryonated eggs) Temb readings were recorded. For the determination of Temb, 26 rather than 32 implanted embryonated eggs (4 per each of 8 tray levels) were used, and this was due to the elimination of eggs that contained embryos that failed to hatch by d 21.5 of incubation or because of technical errors in the temperature determination process. Subsequently, differences between embryonated and nonembryonated egg internal (air cell) temperatures (ΔT) were calculated every 12 h by subtracting the mean value of Tnem readings (n = 16) from the mean value of Temb readings (n = 16; ΔT = Temb – Tnem).

### Eggshell Water Vapor Conductance

Average daily incubational weight (moisture) loss (EWL; mg) values of embryonated and nonembryonated eggs between 10.5 and 18 d of incubation were determined for the subsequent calculation of the respective percentage of EWL values. The 10.5 to 18 d mean values of Tinc and Temb along with the incubator RH and atmospheric pressure values were used for the calculation of ΔPH2O. Subsequently, GH2O [GH2O = EWL (mg)/ΔPH2O (Torr)] and gH2O [gH2O = GH2O/set egg weight (g)] of embryonated and nonembryonated eggs were calculated using the procedures and equations described by Ar et al. (1974) and Ar and Rahn (1978) and modified by Pulikanti et al. (2011b). Based on the hatch monitor data between 18.5 and 21.5 d of incubation, incubation length (in days) of individual embryonated eggs were determined. Furthermore, the GH2O constants (KHi2O) of the embryonated eggs were calculated by using the formula [KH2O = GH2O × incubation length (d)/set egg weight (g)] as described by Ar et al. (1974) and Ar and Rahn (1978).

### Statistical Analysis

For the analyses of Text, Tnem, Temb, and ΔT, each tray level was considered as a replicate unit. All data were analyzed using version 9.1 SAS Institute (2003). The REG procedure was used for regression analyses of Tinc, Tlog, Text, Tnem, Temb, and ΔT over the days of incubation, and the MEANS procedure was used to determine CV values for these parameters. A repeated measures analysis was employed using the MIXED model that accounted for the variability among the trays to examine the influence of the days of incubation, type of temperature measurement (Text, Tnem, and Temb), and the interaction of the days of incubation and the type of temperature measurement on the temperature. The MIXED procedure was also used for a one-way ANOVA in set egg weight, percentage of EWL, ΔPH2O, GH2O, and gH2O between nonembryonated and embryonated eggs. Least squares means were compared in the event of significant global effects (Steel and Torrie, 1980). Furthermore, global effects, regression trends, and differences among least squares means were considered significant at $P \leq 0.05$.

### RESULTS AND DISCUSSION

An approximate 90.6% (29 out of 32 total) embryo survivability was observed in the implanted embryonated eggs. The mean values of the percentage of EWL in nonembryonated and embryonated implanted eggs for the 10.5 to 18 d incubational period were 0.54 ± 0.03 and 0.54 ± 0.02%, respectively (Table 1). The mean percentage of EWL of implanted embryonated Ross × Ross 708 eggs in this experiment was in close comparison to that (0.55 ± 0.015%) reported by Pulikanti et al. (2011b) in embryonated Ross × Ross 308 broiler hatching eggs. The mean values of Tinc, Tlog, Text, Tnem, Temb, and ΔT for the 10.5 to 18 d incubational period in the current study were 37.5 ± 0.02, 37.4 ± 0.02, 37.6 ± 0.04, 37.6 ± 0.03, 38.1 ± 0.05, and 0.14 ± 0.032°C, respectively (Table 2). The 10.5 to 18 d mean value of Tnem were numerically higher (approximately 0.6°C) than those for all other temperature measurements, including Tinc, Tlog, Text, and Temb (Table 2), suggesting that the transponders inserted in the air cells of the embryonated eggs provided a closer estimate of the embryo temperature. The 10.5 to 18 d mean values of Tnem and Temb were similar to each other, but those were numerically higher than the 10.5 to 18 d mean values of Tinc and Tlog (Table 2). This indicates that the external microenvironmental temperatures of the incubating embryonated eggs may be effectively determined by the use of transponders that are contained within water vials or that are inserted in the air cells of nonembryonated eggs located within 5 cm of the embryonated eggs. However, the higher CV of Text compared with that of Tnem indicates that the transponders present in the water vials were more sensitive to minute fluctuations in the external microenvironmental temperatures of the...
embryonated eggs. Such temperature fluctuations in the immediate vicinity of an incubating embryonated egg may be attributable to changes in the level of metabolic heat that are produced from the actively metabolizing and rapidly growing broiler embryo during the latter half of incubation.

More importantly, a significant interaction ($P \leq 0.001$) of days of incubation $\times$ type of temperature measurement ($T_{\text{emb}}$, $T_{\text{nem}}$, and $T_{\text{inc}}$) was observed for temperature. The values of $T_{\text{ext}}$, $T_{\text{nem}}$, and $T_{\text{emb}}$ that were observed every 12 h are provided in Table 3. Beginning on d 13 of incubation, $T_{\text{emb}}$ consistently remained significantly higher than $T_{\text{ext}}$ and $T_{\text{nem}}$. These observations further support the importance of air cell transponder implantation for a more accurate estimation of broiler embryo temperature during incubation.

Although $T_{\text{inc}}$ ($CV = 0.18$) and $T_{\log}$ ($CV = 0.17$) showed similar levels of variation between 10.5 and 18 d of incubation (Table 2; Figure 1), the 12-h mean values of $T_{\log}$ in that time interval were calculated using temperature readings that were taken every 5 min from 3 data loggers that covered the entire area inside the incubator. Conversely, $T_{\text{inc}}$ was determined every 12 h with the use of a single incubator dry bulb thermometer that was located at the top right-hand corner of the incubator. Therefore, $T_{\log}$ was considered to be a more reliable indicator of overall incubation temperature (temperature of the air circulating inside the incubator) when compared with $T_{\text{inc}}$. Nevertheless, when comparing the use of $T_{\text{inc}}$ or $T_{\log}$ with $T_{\text{ext}}$ or $T_{\text{nem}}$, this study further suggests that a single factory-installed dry bulb thermometer as a standard component in commercial incubators, or the use of data loggers that are widely dispersed within an incubator, may not be sufficient in providing an accurate estimation of the external micro-environmental temperature of an incubating egg.

The mean values of $T_{\text{ext}}$ and $T_{\text{emb}}$ over the 10.5 to 18 d incubational period for the Ross $\times$ Ross 708 eggs are shown in Table 3. These results suggest that the use of $T_{\log}$ rather than $T_{\text{ext}}$ or $T_{\text{nem}}$ may provide a more accurate indication of the temperature field experienced by developing embryos in an incubator.

### Table 1. Mean values, incubation length in days, and conductance constants ($K_{\text{H}_2\text{O}}$) of embryonated Ross $\times$ Ross 708 broiler hatching eggs between 10.5 and 18 d of incubation

<table>
<thead>
<tr>
<th>Item</th>
<th>Nonembryonated egg</th>
<th>Embryonated egg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set egg weight (g)</td>
<td>55.6 ± 0.74$^d$</td>
<td>57.6 ± 0.46$^a$</td>
</tr>
<tr>
<td>$\Delta P_{\text{H}_2\text{O}}$</td>
<td>20.2 ± 0.20</td>
<td>20.2 ± 0.22</td>
</tr>
<tr>
<td>EWL (%)</td>
<td>0.54 ± 0.026</td>
<td>0.54 ± 0.019</td>
</tr>
<tr>
<td>$G_{\text{H}_2\text{O}}$</td>
<td>14.0 ± 0.69</td>
<td>14.1 ± 0.56</td>
</tr>
<tr>
<td>$\varepsilon_{\text{H}_2\text{O}}$</td>
<td>25.2 ± 1.29</td>
<td>25.0 ± 0.96</td>
</tr>
<tr>
<td>Incubation length (d)</td>
<td>—</td>
<td>20.8 ± 0.07</td>
</tr>
<tr>
<td>$K_{\text{H}_2\text{O}}$</td>
<td>—</td>
<td>5.20 ± 0.206</td>
</tr>
</tbody>
</table>

$^a$Means within a row with no common superscript differ significantly ($P \leq 0.05$).

$^b$A total of 16 nonembryonated eggs (2 nonembryonated eggs on each of 8 incubator tray levels) were used for the calculation of the mean values.

$^c$A total of 26 embryonated eggs were used for the calculation of the mean values.

### Table 2. Mean values of temperature readings from incubator dry bulb thermometer ($T_{\text{inc}}$) and data loggers ($T_{\log}$); and transponders present in water vials ($T_{\text{ext}}$) and nonembryonated ($T_{\text{nem}}$) and embryonated egg air cells ($T_{\text{emb}}$), between 10.5 and 18 d of incubation$^1$

<table>
<thead>
<tr>
<th>Item</th>
<th>Mean (°C)</th>
<th>SEM</th>
<th>N$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{inc}}$</td>
<td>37.5</td>
<td>0.02</td>
<td>16</td>
</tr>
<tr>
<td>$T_{\log}$</td>
<td>37.4</td>
<td>0.02</td>
<td>6,912</td>
</tr>
<tr>
<td>$T_{\text{ext}}$</td>
<td>37.6</td>
<td>0.04</td>
<td>256</td>
</tr>
<tr>
<td>$T_{\text{nem}}$</td>
<td>37.6</td>
<td>0.03</td>
<td>256</td>
</tr>
<tr>
<td>$T_{\text{emb}}$</td>
<td>38.1</td>
<td>0.05</td>
<td>416</td>
</tr>
</tbody>
</table>

$^1$A total of approximately 16 transponders present in water vials ($T_{\text{ext}}$) and nonembryonated ($T_{\text{nem}}$) and embryonated egg air cells ($T_{\text{emb}}$) was used in the calculation of the mean values.

$^2$Represents the total number of readings used in the calculation of the mean and SEM for each parameter.
reported in this study (Table 2) were in close compari-
son to those reported for Ross × Ross 308 eggs by
Pulikanti et al. (2011b). The mean values of Text and
Temb for the 10.5 to 18.5 d incubational period, as re-
ported by Pulikanti et al. (2011b), were 37.1 ± 0.03
and 37.8 ± 0.09°C, respectively. Close comparisons of
the mean values of the percentage of EWL, Text, and
Temb observed in the current experiment with those
reported by Pulikanti et al. (2011b) indicate that the
eggs in these 2 experiments were subjected to similar
incubational conditions, which would have caused simi-
lar physiological growth responses in the embryos.

Between 10.5 and 18 d of incubation, significant posi-
tive regression trends were observed for Temb and
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the mean values of the percentage of EWL, Text, and
Temb observed in the current experiment with those
reported by Pulikanti et al. (2011b) indicate that the
eggs in these 2 experiments were subjected to similar
incubational conditions, which would have caused simi-
lar physiological growth responses in the embryos.

Between 10.5 and 18 d of incubation, significant posi-
tive regression trends were observed for Tinc and
DT; whereas a significant negative regression trend was ob-
served for Tnem (Table 4; Figures 1 and 2). The vari-
ations in Tinc, Tlog, Text, Tnem, and Temb every 12 h
between 10.5 and 18 d of incubation are presented in
graphical form in Figure 1. The physiological basis for
the significant negative regression of Tnem over days of
incubation is unclear. Nonetheless, the regression val-
ues (Table 4) and the associated graphs (Figures 1 and
2) of the different types of temperature measurements
indicated that Temb showed a significant progressive
increase between 10.5 and 18 d of incubation, which
resulted in a significant difference between Temb and
Tnem. Similarly, the internal egg and eggshell tempera-
tures for turkey eggs reported by French (1997) showed
progressive increases during the second half of incuba-
tion. However, the eggshell temperatures in that experi-
ment were observed to remain consistently lower and
more variable than the corresponding internal egg tem-
peratures. This could be attributed to the fact that egg-
shell temperatures are more susceptible to variations
in the thermal conductivity of the eggshell and the air
flow around the egg (Eren Ozcan et al., 2010; Lourens
et al., 2011). In the current study, Tinc, Tlog, and Tnem
displayed minimal variations (CV = 0.18, 0.17, and
0.23, respectively), whereas Text showed the greatest
variation (CV = 0.42; Table 4). Although the mean
values of Text and Tnem were similar to each other, the
variable pattern of Text over a relatively broad range of
temperatures would indicate that Text was more sensi-
tive than were Tinc, Tlog, and Tnem to minute fluctua-
tions in the temperatures of the microenvironment sur-
rounding the incubating embryonated egg. The higher
sensitivity of the transponders present in the water
vials to variations in external microenvironment egg
temperatures may be attributable to the smaller size
and higher surface area-to-volume ratio of the water
vials compared with that of the nonembryonated eggs.

The progressive increases in Temb between 10.5 and
18 d of incubation is an effect that results from the
continued increase in embryo metabolism (Janke et al.,
2002) and the fact that embryonic tissue continues to
occupy a greater proportion of the egg’s interior (Ro-
manoff, 1960; Parkhurst and Mountney, 1988). Sub-
sequently, metabolic heat production by the embryo
increases during the later part of incubation (Sturkie,
1965; Janke et al., 2002). According to De Smit et al.
(2008), during the first half of incubation (d 1–10.5),
chicken embryos undergo tissue differentiation and or-
gan formation, during which time they require energy
from an external source, and therefore, continuously
absorb heat from the air circulating inside the incuba-
tor. De Smit et al. (2008) also suggested that during
the second half of incubation (d 10.5–21), the embryos un-
dergo rapid growth and development and actively me-
tabolize available nutrients in the egg for this purpose.
Consequently, embryos tend to lose excess metabolic heat to the surrounding atmosphere inside the incubator. The relative advantage of using the transponders for determination of internal egg (air cell) temperatures was clearly evident from their efficient and closer reflection of the progressive increases in the corresponding embryonic temperatures during the later part of incubation. Furthermore, the transponders used in the current experiment were capable of detecting the minute temperature differences that existed between Temb and Tinc at each 12-h time period between 10.5 and 18 d of incubation. These findings support the suggestions by Lourens et al. (2005), that embryo temperature can be noticeably different from the incubator temperature at certain periods during incubation.

For the 10.5 to 18-d incubational period in the present study, mean values of $G_{H_2O}$ and $g_{H_2O}$ in embryonated eggs were 14.4 ± 0.56 mg of H$_2$O/d per Torr and 25.0 ± 0.96 mg of H$_2$O/d per Torr per 100 g, respectively; whereas, those of nonembryonated eggs were 14.0 ± 0.69 mg of H$_2$O/d per Torr and 25.2 ± 1.29 mg of H$_2$O/d per Torr per 100 g, respectively (Table 1). The close comparison of the mean values of $G_{H_2O}$ and $g_{H_2O}$ between nonembryonated and embryonated eggs in the current experiment support the potential use of nonembryonated eggs of known shell properties (calibrated eggs) for an indirect estimation of the conductance parameters of embryonated eggs, as suggested by previous researchers (Tullett, 1982; Visschedijk et al., 1985). The mean $G_{H_2O}$ value of Ross × Ross 308 broiler hatching eggs reported by Pulikanti et al. (2011b) was 13.9 ± 0.47 mg of H$_2$O/d per Torr; whereas the mean $G_{H_2O}$ values reported by Ar et al. (1974) and Ar and Rahn (1978) for Gallus gallus (domestic chicken) eggs were 14.4 ± 2.38 and 14.4 (SEM not reported) mg of H$_2$O/d per Torr, respectively. The mean $g_{H_2O}$ value reported by Pulikanti et al. (2011b) in Ross × Ross 308 broiler hatching eggs was 24.5 ± 0.75 mg of H$_2$O/d per Torr per 100 g, whereas the mean $g_{H_2O}$ values of Gallus gallus eggs reported by Ar et al. (1974) and Ar and Rahn (1978) were 26.5 ± 3.36 and 26.7 mg of H$_2$O/d per Torr per 100 g, respectively. As $g_{H_2O}$ is calculated by accounting for variations in egg weight, it is used as a more standardized expression of eggshell conductance when compared with $G_{H_2O}$. It was not possible to statistically compare the $g_{H_2O}$ values of different strains or species among the different experiments. However, the $g_{H_2O}$ values of Ross × Ross 708 broiler hatching eggs reported in the current experiment and of Ross × Ross 308 eggs in a similar experiment by Pulikanti et al. (2011b) were closely comparable to each other. Nevertheless, the $g_{H_2O}$ values of Ross × Ross 308 and 708 eggs were not as comparable to the mean $g_{H_2O}$ value of Gallus gallus eggs reported by Ar et al. (1974) and Ar and Rahn (1978). This difference may be attributable to differences in breed or strain and in the methodology.

**Table 4.** Regression values (adjusted $R^2$, slope, Y-intercept, CV, and $P$-value) from temperature and transponder readings over 10.5 to 18 d of incubation$^{1,2}$

<table>
<thead>
<tr>
<th>Item</th>
<th>$T_{inc}$</th>
<th>$T_{log}$</th>
<th>$T_{ext}$</th>
<th>$T_{nem}$</th>
<th>$T_{emb}$</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted $R^2$</td>
<td>0.07</td>
<td>−0.03</td>
<td>−0.07</td>
<td>0.38</td>
<td>0.77</td>
<td>0.86</td>
</tr>
<tr>
<td>Slope</td>
<td>−0.01</td>
<td>0.01</td>
<td>−0.001</td>
<td>−0.03</td>
<td>0.06</td>
<td>0.10</td>
</tr>
<tr>
<td>Y-intercept</td>
<td>37.6</td>
<td>37.3</td>
<td>37.6</td>
<td>38.1</td>
<td>37.2</td>
<td>−0.93</td>
</tr>
<tr>
<td>CV</td>
<td>0.18</td>
<td>0.17</td>
<td>0.42</td>
<td>0.23</td>
<td>0.22</td>
<td>0.06</td>
</tr>
<tr>
<td>$P$-value</td>
<td>≤0.160</td>
<td>≤0.460</td>
<td>≤0.940</td>
<td>≤0.006</td>
<td>≤0.001</td>
<td>≤0.001</td>
</tr>
</tbody>
</table>

$^{1}$ $T_{inc}$ = temperature reading from incubator dry bulb thermometer; $T_{log}$ = temperature reading from data loggers; $T_{ext}$ = transponder reading from water vials; $T_{nem}$ = transponder reading from nonembryonated eggs; $T_{emb}$ = transponder reading from embryonated eggs; and $\Delta T$ = differences between 12 h mean values of $T_{emb}$ and $T_{nem}$.

$^{2}$ $T_{log}$ was recorded every 5 min, whereas $T_{inc}$, $T_{ext}$, $T_{nem}$, and $T_{emb}$ were recorded and $\Delta T$ was calculated every 12 h. For $\Delta T$ and each type of temperature measurement ($T_{inc}$, $T_{log}$, $T_{ext}$, $T_{nem}$, and $T_{emb}$), 16 mean values (sixteen 12-h periods between 10.5 and 18 d of incubation) were used for regression analysis.

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**Figure 2.** Semicircadian variable patterns between 10.5 and 18 d of incubation for differences in the mean embryonated and nonembryonated egg air cell transponder temperature readings. Each of the 16 mean values for the differences represents the difference between the mean embryonated and nonembryonated egg readings recorded in that 12-h time period.
gies used in the different experiments, including differences in the devices used for the determination of embryo temperature.

The mean values of incubation length and $K_{H_2O}$ in embryonated Ross × Ross 708 broiler hatching eggs were $20.8 \pm 0.07$ d and $5.20 \pm 0.205$, respectively (Table 1). Although, it was not possible to statistically examine differences in the respective $K_{H_2O}$ values reported in the current experiment with those reported by Ar et al. (1974) and Ar and Rahn (1978), the mean value of $K_{H_2O}$ reported in the current experiment was numerically different from the $K_{H_2O}$ value (5.61) of *Gallus gallus* eggs reported by Ar et al. (1974) and Ar and Rahn (1978). The potential differences in $K_{H_2O}$ values between the eggs of different species, breeds, or strains could be attributed to the associated differences in their eggshell porosities (Washburn, 1990).

In conclusion, transponders implanted in the air cells of embryonated broiler hatching eggs were shown to be efficient in detecting incubational variations in the embryonic temperature between 10.5 and 18 d of incubation and for the subsequent calculation of $G_{H_2O}$, $E_{H_2O}$, and $K_{H_2O}$. The progressive increases in $T_{emb}$ and $\Delta T$ values between 10.5 and 18 d of incubation reflected an increase in metabolic heat production by the growing broiler embryo during the latter half of incubation. Transponders placed in water vials or that are inserted into nonembryonated egg air cells may be more reliable indicators of the external microenvironmental temperatures of incubating embryonated eggs than are incubator dry bulb thermometer or data logger temperature readings. Transponders in water-filled vials may also be more reliable than transponders implanted in the air cells of nonembryonated eggs due to their higher sensitivity to minute temperature fluctuations in the immediate vicinity of a rapidly growing and actively metabolizing broiler embryo. It can also be inferred that nonembryonated eggs may be used as calibrated eggs for the indirect determination of $G_{H_2O}$ and $E_{H_2O}$ of embryonated eggs, whereas the determination of $K_{H_2O}$ necessitates the use of embryonated eggs.

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**REFERENCES**


