REVIEW

# The ingestible telemetric body core temperature sensor: a review of validity and exercise applications

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An ingestible telemetric temperature sensor for measuring body core temperature ($T_c$) was first described 45 years ago, although the method has only recently gained widespread use for exercise applications. This review aims to (1) use Bland and Altman's limits of agreement (LoA) method as a basis for quantitatively reviewing the agreement between intestinal sensor temperature ($T_{intestinal}$), oesophageal temperature ($T_{oesophageal}$) and rectal temperature ($T_{rectal}$) across numerous previously published validation studies; (2) review factors that may affect agreement; and (3) review the application of this technology in field-based exercise studies. The agreement between $T_{intestinal}$ and $T_{oesophageal}$ is suggested to meet our delimitation for an acceptable level of agreement (ie, systematic bias $<0.1^{\circ}C$ and 95% LoA within $\pm 0.4^{\circ}C$). The agreement between $T_{intestinal}$ and $T_{rectal}$ shows a significant systematic bias $>0.1^{\circ}C$, although the 95% LoA is acceptable. $T_{intestinal}$ responds less rapidly than $T_{oesophageal}$ at the start or cessation of exercise or to a change in exercise intensity, but more rapidly than $T_{rectal}$. When using this technology, care should be taken to ensure adequate control over sensor calibration and data correction, timing of ingestion and electromagnetic interference. The ingestible sensor has been applied successfully in numerous sport and occupational applications such as the continuous measurement of $T_c$ in deep sea saturation divers, distance runners and soldiers undertaking sustained military training exercises. It is concluded that the ingestible telemetric temperature sensor represents a valid index of $T_c$ and shows excellent utility for ambulatory field-based applications.

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Body core temperature ($T_c$) measurement is fundamental to the study of human temperature regulation during exercise.[1] Core temperature is implicated in heat- and cold-related illnesses[2–4] and can influence exercise performance.[5] Yet, the term ''core'' does not describe a specific anatomical location, and no single regional internal temperature provides an index of the average internal body temperature; the body interior is not at one uniform temperature and the thermoregulatory centre receives temperature inputs from many internal sites.[1 6] The temperature of blood in the pulmonary artery is considered the best representation of the average internal temperature of the body as the mixed venous blood has returned from both the core and periphery and is almost identical to arterial blood.[6 7] As this site is not accessible, $T_c$ is often measured at the oesophagus, rectum, mouth or external auditory meatus/tympanic membrane.[1 6 7] An ideal site for $T_c$ measurement is one that is convenient, unaffected by environmental conditions, responds rapidly and quantitatively reflects small changes in central blood temperature.[1] Oesophageal temperature ($T_{oesophageal}$) at the level of the left atrium provides the closest agreement with central blood and is considered the best available index of $T_c$ for exercise studies.[1 6 7] Rectal temperature ($T_{rectal}$) is the most widely used index of $T_c$ in exercise studies, yet its slow response to changes in exercise intensity and central blood temperature means that $T_{rectal}$ is only considered an acceptable index of $T_c$ during steady-state conditions.[1 6 7]

An alternative method of $T_c$ measurement, particularly suited to field-based ambulatory applications, is the ingestible telemetric temperature ''pill'' or ''capsule''. An ingestible ''radio pill'' was first described >45 years ago,[8] with technological modifications on this theme continuing to the present.[9–11] The sensor is ingested and transmits a temperature signal, relative to the surrounding gastrointestinal temperature ($T_{intestinal}$), by radio wave to an external receiver for data logging or instant display. Presently, there are two commercially available ingestible temperature sensor and receiver systems: (1) CorTemp (weight = 2.75 g, length = 23 mm, diameter = 10.25 mm) and external ambulatory data receiver (CorTemp HQ Inc., Palmetto, Florida, USA); and (2) VitalSense ingestible telemetric temperature sensor (weight = 1.75 g, length = 21.9 mm, diameter = 8.5 mm) and external ambulatory data receiver (VitalSense, Mini Mitter Co., Inc., Bend, Oregon, USA).

A number of small studies (ie, sample sizes ranging from 4 to 11) have now investigated the validity of the ingestible sensor as an index of $T_c$ and the method is gaining widespread use, particularly in field-based studies. Therefore, we aim to use Bland and Altman's limits of agreement (LoA) method as a basis for quantitatively reviewing the agreement between $T_{intestinal}$, $T_{oesophageal}$ and $T_{rectal}$ across numerous previously published validation studies. Our objective is to provide a clear overview of the results of the numerous validation studies and establish the existence of any consistent differences between measurement sites. We further aim to review factors that may

**Abbreviations:** LoA, limits of agreement; RMSD, root mean-squared deviation

**Table 1** Summary of studies comparing the agreement between core temperature measurements recorded simultaneously from an ingestible telemetric temperature sensor and an oesophageal and/or rectal probe

| Authors | Comparison | Calibration | Ingestion | Sample | Protocol | Environment | Analysis | Valid |
|---|---|---|---|---|---|---|---|---|
| Gibson *et al*[9] | Oesophageal, rectal | Yes, method NS | 30 min | 7 M | Resting immersion, cycling | W = 41 and 10°C (rest), DB = 25°C (cycling) | Regression, RMSD | Yes |
| Fox *et al*[20] | Oesophageal, rectal | Water bath method NS | NS | NS | Rest, immersion, exercise | DB = NS, W = NS | NS | Yes |
| Livingstone *et al*[12] | Oesophageal, rectal | NS | NS | 5 M | Rest, walking | DB = 24–26°C (rest); DB = −32°C, V = 11 km/h (rest, walking) | NS | Yes |
| Kolka *et al*[13] | Oesophageal, rectal | NS | 2 (0.5) h | 8 M | Cycling | DB = 29.5°C | ANOVA | No |
| Sparling *et al*[14] | Rectal | Water bath, corrections applied | 3–4, 8–9 h | 6 M | Running, cycling | DB = 20.8°C, RH = 56% | t tests | No |
| Kolka *et al*[15] | Oesophageal | Water bath, inaccurate sensors eliminated | 2 (0.5) h | 4 F | Walking | DB = 30°C | Regression | Yes |
| O'Brien *et al*[16] | Oesophageal, rectal | Water bath, regression equation applied | 12 h | 9 (5 F, 4M) | Resting immersion, cycling immersion | W = 18 and 36°C | ANOVA, RMSD | Yes |
| Lee *et al*[17] | Oesophageal, rectal | Water bath, regression equation applied | 6 h | 7 (2F, 5M) | Rest, cycling | NS | ANOVA | Yes |
| Ducharme *et al*[21] | Rectal | NS | 40 min | 11 M | 36 h rest, walking, running | DB = 30°C, RH = 50% | NS | Yes |
| Edwards *et al*[18] | Rectal | NS | 1 h before sleep | 8 M | Circadian monitoring | NS | Correlation, cosinor, LoA | Yes |
| McKenzie and Osgood[11] | Rectal | Yes, method NS | NS | 10 (4F, 6M) | Circadian monitoring | NS | Regression, ANOVA | Yes |
| Gant *et al*[19] | Rectal | Water bath, method NS | 10 h | 10 M, 9 M | Intermittent shuttle running | NS | ANOVA, LoA, ICC, CV | Yes |

ANOVA, analysis of variance; CV, coefficient of variation; DB, dry bulb air temperature; F, female; ICC, intraclass correlation coefficient; LoA, limits of agreement; M, male; NS, information not stated; RH, % relative humidity; RMSD, root mean squared deviation; V, km/h wind velocity; W, water temperature.
Values are mean (SD) or range. Comparison, method(s) against which intestinal temperature compared.
Ingestion, timing of sensor ingestion in hours or minutes before start of exercise or data collection.
Validity, decision of authors regarding acceptability of intestinal temperature as a valid index of $T_C$.
Systems used: Custom-made ingestible temperature-sensing radio pill and receiver system developed by the National Institute for Medical Research, UK.[20] Custom-made ingestible temperature sensing radio pill and receiver system developed by the Royal Air Force Institute of Aviation Medicine, UK.[9] Ingestible temperature-sensing radio pill and receiver system of unknown origin.[12] Commercially available CorTemp system consisting of ingestible telemetric temperature sensor and data recorder (HQ Inc., Palmetto, Florida, USA) developed by the Applied Physics Laboratory, Johns Hopkins University and the National Aeronautics and Space Administration, USA.[13 15 17–19] System consisting of CorTemp ingestible telemetric temperature sensor (HQ Inc.) and compact data receiver/logger (BBN Systems and Technologies, Massachusetts, USA).[16] Commercially available VitalSense system consisting of Jonah ingestible temperature sensor and telemetric monitor (Mini Mitter Co., Inc., Bend, Oregon, USA).[11] System used not stated.[21]

affect agreement and also to review the application of this technology in field-based studies.

## METHODS

Ten peer reviewed full publications[9 11–19] and two abstract publications[20 21] comparing $T_{intestinal}$ with $T_{oesophageal}$ and/or $T_{rectal}$ were reviewed (table 1). LoA was selected as the most appropriate statistical method for assessing agreement between a new measurement technique (eg, ingestible telemetric temperature sensor) and an established technique (eg, oesophageal or rectal probe).[22 23] Although only two of the validation studies in table 1 used the LoA method,[18 19] individual data were available from three further studies,[13 14 17] allowing calculation of LoA for 5 of the 12 validation studies, and allowing a standardised quantitative comparison of agreement across these studies. The method provides a measure of systematic bias (ie, general trend for measurements to be different in a positive or negative direction), evidence of heteroscedasticity (ie, whether differences are related to the magnitude of the measurements) and a 95% random error component (ie, boundaries accounting for 95% of differences between methods).[22 23] Thus, LoA represents the largest difference between methods that can be expected for most (ie, 95%) individuals in the studied population. In this review, LoA data form the basis for assessing the level of agreement between $T_{intestinal}$, $T_{oesophageal}$ or $T_{rectal}$ before the data are evaluated in the context of findings from the remaining validation studies and conclusions are drawn regarding the relationship of $T_{intestinal}$ to that of $T_{oesophageal}$ and $T_{rectal}$. Nine further studies using ingestible sensors in sports or occupational settings involving physical activity were reviewed to assess the utility of the technology for field-based exercise applications.[24–32]

From the outset, it should be noted that surprisingly few validation studies have delimited an acceptable level of agreement between methods. Gant *et al*[19] delimited a systematic bias of >0.1°C between $T_{intestinal}$ and $T_{rectal}$ as being practically important in affecting decisions made on an individual's thermal status. Furthermore, these authors stated that 95% of the differences between methods should fall within ±0.3°C.[19] Our review indicates the lowest values for 95% LoA to be ±0.37°C for $T_{intestinal}-T_{oesophageal}$[17] and ±0.22°C for $T_{intestinal}$ and $T_{rectal}$.[19] Therefore, we delimit an acceptable level of agreement as a bias <0.1°C and 95% LoA within ±0.4°C.

## VALIDITY AND RELIABILITY OF THE INGESTIBLE TEMPERATURE SENSOR

Table 1 shows that 10 of the 12 validation studies (83%) report levels of agreement supporting the conclusion that $T_{intestinal}$ provides a valid index of $T_c$.[9 11 15–21] Comparisons have ranged in duration from acute, lasting up to 3 h,[17 19 20] to long-term, lasting for 24 h,[18] 36 h[21] and up to 136 h.[11] Agreement has been assessed by simultaneous comparisons of $T_c$ magnitude at discrete time points within a protocol[12–14 17] and/or by a comparison of $T_c$ responses encompassing the whole protocol.[9 11 15 16 18 19] For example, in the study of Lee *et al*[17] shown in

figure 1, $T_{intestinal}$, $T_{oesophageal}$ and $T_{rectal}$ were compared at several discrete time points throughout an experimental protocol—that is, before and after 20 min of rest, after 20 min of cycling at 40% peak oxygen consumption ($Vo_{2peak}$), after 20 min of cycling at 65% $Vo_{2peak}$, and after 20 min of passive recovery. Several studies have also compared intestinal, oesophageal and rectal sites for their responsiveness (eg, time for a 0.1℃ change) and/or rate of change (eg, ℃/min) at the start or cessation of exercise or in response to a change in exercise intensity.[9 13 17 19]

## Oesophageal versus intestinal temperature

Seven studies in table 1 compared $T_{oesophageal}$ with $T_{intestinal}$, although LoA data were available for only two studies.[13 17] The data of Kolka *et al*[13] showed 95% of $T_{oesophageal}$ readings to fall 0.45℃ below to 0.41℃ above $T_{intestinal}$, similar to the data of Lee *et al*,[18] which showed 95% LoA of −0.40℃ to 0.34℃ (table 2). Both study data show no significant ($p>0.05$) systematic bias in the relationship between $T_{oesophageal}$ and $T_{intestinal}$ (ie, systematic bias of −0.02℃ and −0.03℃, respectively). Thus, LoA data show no evidence of a consistent difference between $T_{oesophageal}$ and $T_{intestinal}$, with $T_{oesophageal}$ expected to fall within 0.45℃ below to 0.41℃ above $T_{intestinal}$ for a new individual from the studied population. Despite our reanalysis of the data of Kolka *et al*[13] showing agreement between $T_{oesophageal}$ and $T_{intestinal}$ approaching our delimited acceptable level (i.e, <0.4℃), the authors rejected the use of $T_{intestinal}$ for research purposes. They observed $T_{intestinal}$ fluctuations of 0.2–0.3℃ in two of their eight subjects and hypothesised that the changing anatomical location of the intestinal sensor during gastrointestinal transit could potentially confound the $T_{oesophageal}$–$T_{intestinal}$ relationship.

Supporting the LoA data, Gibson *et al*[9] observed no evidence of a statistically significant systematic bias between $T_{oesophageal}$ and $T_{intestinal}$ at discrete time points during their experimental protocols, despite evident variability between the two temperatures sites. O'Brien *et al*[16] observed no significant differences between $T_{oesophageal}$ and $T_{intestinal}$ during 3 h resting and exercise experiments in cold water with overall root mean-squared deviations (RMSDs) of 0.23℃ (0.04)℃ and 0.24℃ (0.02)℃, respectively. However, during resting and exercise experiments in warm water, $T_{intestinal}$ was consistently and significantly higher than $T_{oesophageal}$, although the RMSD (ie, 0.25℃ (0.05)℃ and 0.26℃ (0.03)℃, respectively) remained similar to those observed during the experiments in cold water. Livingstone *et al*[12] also reported $T_{intestinal}$ to be consistently higher (<0.5℃) than $T_{oesophageal}$ during 90 min protocols of rest in neutral and cold environments, and low-intensity walking in a cold environment. However, the authors did not report whether this consistent bias was statistically significant. In summary, an acceptable level of agreement has been concluded in six of the seven studies comparing $T_{oesophageal}$ and $T_{intestinal}$ at discrete time points or when comparing responses over a complete experiment. Level of agreement data and data from varied statistical analyses show variability within ±0.5℃ with a tendency for $T_{intestinal}$ to be higher than $T_{oesophageal}$. The lowest level of agreement was ±0.37℃ with no significant bias, which is within our acceptable limits.

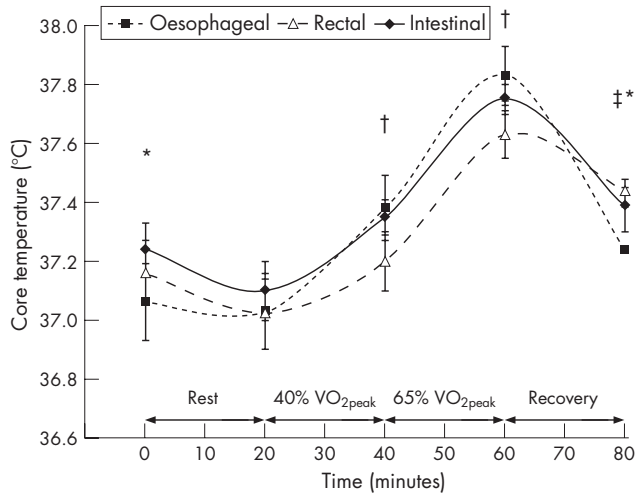


**Figure 1** Oesophageal, rectal and intestinal temperatures measured simultaneously during rest, submaximal supine cycling exercise at 40% peak oxygen consumption ($Vo_{2peak}$) and 65% $Vo_{2peak}$, and during passive recovery. Values are mean (SE). *Intestinal temperature significantly higher than oesophageal temperature ($p<0.05$), †rectal temperature significantly lower than oesophageal temperature ($p<0.05$), ‡rectal temperature significantly higher than oesophageal temperature ($p<0.05$). Redrawn from the data of Lee *et al*[17]

## Responsiveness of $T_{oesophageal}$ versus $T_{intestinal}$

Table 3 shows the lower rate of change (℃/min) and concomitant longer duration for $T_{intestinal}$ to achieve a 0.1℃ threshold change in temperature than $T_{oesophageal}$ at the onset or cessation of exercise.[13 17] Without exception, the data in table 3 show a slower response of $T_{intestinal}$ versus $T_{oesophageal}$ to changes in exercise intensity; however, differences between the two sites do not always reach statistical significance.

## Rectal versus intestinal temperature

Of the 12 studies in table 1, 11 compared $T_{rectal}$ and $T_{intestinal}$, with 5 studies using $T_{rectal}$ as the sole criterion measure of $T_c$.[11 14 18–19 21] LoA data were available from five studies,[13 14 17–19] with each set of study data showing a statistically significant systematic bias between $T_{rectal}$ and $T_{intestinal}$ (table 2). Mixed findings were revealed regarding the positive or negative direction of the bias. Whereas two earlier studies showed $T_{rectal}$ to read significantly ($p<0.05$) and consistently higher (ie, 0.18℃ (0.47)℃ and 0.76℃ (0.68)℃) than $T_{intestinal}$,[13 14] three later studies showed $T_{rectal}$ to read significantly ($p<0.05$) and consistently lower (ie, −0.07℃ (0.34)℃, −0.20℃ (0.40)℃ and −0.15℃ (0.22)℃) than $T_{intestinal}$.[17–19] These consistent findings suggest a practically significant bias (ie, >0.1℃) between $T_{rectal}$ and $T_{intestinal}$, which needs to be accounted for when interpreting an individual's thermal status.[19]

The data of Kolka *et al*[13] suggest that $T_{rectal}$ may range from 0.27℃ below to 0.65℃ above $T_{intestinal}$, whereas the data of Sparling *et al*[14] suggest that $T_{rectal}$ may range from 0.08℃ to 1.44℃ above $T_{intestinal}$. Ducharme *et al*[21] reported absolute differences between $T_{rectal}$ and $T_{intestinal}$ of magnitude similar to the LoA data of Kolka *et al*[13] during periods of 2 h walking and running exercise in the heat. Rectal temperature was significantly higher than $T_{intestinal}$ by 0.24 (0.10)℃ during exercise, and although a similar trend remained during periods of rest, the absolute difference (ie, 0.12℃ (0.09)℃) did not reach significance ($p = 0.065$). The data of Sparling *et al*[14] suggested a temperature gradient of large magnitude along the gastrointestinal tract, as the six subjects involved in this study exhibited consistently higher $T_{rectal}$ than $T_{intestinal}$ at rest (0.59℃), during exercise (0.93℃) and during recovery (1.1℃). The only support for $T_{rectal}$–$T_{intestinal}$ differences of this magnitude from the remaining literature is the observation of McKenzie and Osgood,[11] who reported a $T_{rectal}$ 1.79℃ higher than the corresponding $T_{intestinal}$ in a single subject undertaking strenuous exercise in a 36℃ environment. By contrast, the latter three studies in table 2 combined, suggest that $T_{rectal}$ may range from 0.60℃ below to 0.27℃ above $T_{intestinal}$.[17–19] For example, Gant *et al*[19] observed $T_{intestinal}$ to be consistently and significantly higher than $T_{rectal}$ on average by 0.15℃ throughout

**Table 2** Limits of agreement comparison of oesophageal, intestinal and rectal core temperature measurements

| | Oesophageal vs intestinal | | Rectal vs intestinal | | Oesophageal vs rectal | |
|---|---|---|---|---|---|---|
| Reference | LoA | Bias ±95% | LoA | Bias ±95% | LoA | Bias ±95% |
| Kolka *et al*[13] | −0.45 to +0.41 | −0.02 (0.43) | −0.27 to +0.65 | +0.18 (0.47)* | −0.54 to +0.12 | −0.21 (0.33)*† |
| Sparling *et al*[14] | | | +0.08 to +1.44 | +0.76 (0.68)* | | |
| Lee *et al*[17] | −0.40 to +0.34 | −0.03 (0.37) | −0.41 to +0.27 | −0.07 (0.34)* | −0.35 to +0.45 | +0.05 (0.40) |
| Edwards *et al* [18]‡ | | | −0.60 to +0.20 | −0.20 (0.40)* | | |
| Gant *et al*[19] | | | −0.37 to +0.07 | −0.15 (0.22)* | | |

LoA, limits of agreement.
It would be expected with 95% probability that for a new individual from the studied population, the difference between two methods of core temperature measurement will fall within these limits.
Bias ±95% represents the mean difference between the two methods of measurement (eg, mean of oesophageal minus intestinal temperatures) and the SD of the differences multiplied by 1.96 represent 95% of differences.
*Significant systematic bias ($p<0.05$, identified by paired t test) between methods of measurement.
†Significant negative heteroscedasticity ($p<0.05$, identified by Pearson's product moment correlation coefficient).
‡Data represent the mesor of cosinor analysis—that is, mean of the oscillation over 24 h of circadian measurement.

the 60 min of intermittent high-intensity free shuttle running. Such findings are partially supported by O'Brien *et al,*[16] who reported $T_{rectal}$ to be significantly ($p<0.05$) lower than $T_{intestinal}$ on average by 0.43℃ during one of their four experimental trials—that is, 3 h resting in cold water. However, under three other experimental conditions, no statistically significant differences between $T_{rectal}$ and $T_{intestinal}$ were observed.[16] Similarly, McKenzie and Osgood[11] reported no statistically significant difference in the mean of $T_{rectal}$ (36.96℃ (0.16)℃) and $T_{intestinal}$ (36.93℃ (0.15)℃) for 10 subjects over 48.6 (35.5) h.

In summary, LoA data indicate a statistically significant bias between $T_{rectal}$ and $T_{intestinal}$. The direction and magnitude of this bias has varied from study to study. Support for $T_{intestinal}$ exceeding $T_{rectal}$ and vice versa is available from the remaining validation studies, as is support for no consistent bias between the two measurement sites. The non-consistent $T_{rectal}$–$T_{intestinal}$ relationship is not reliably explained by experimental factors. Whether the differences represent a true physiological temperature gradient along the gastrointestinal tract remains to be confirmed and the factors affecting this gradient remain to be elucidated. Substantial evidence suggests that the $T_{rectal}$–$T_{intestinal}$ agreement is acceptable (ie, <0.4℃).

### Responsiveness of $T_{rectal}$ versus $T_{intestinal}$

Table 3 shows the consistent finding that $T_{intestinal}$ is more responsive than $T_{rectal}$ to a change in $T_c$ at the onset or cessation of exercise or to changes in exercise intensity.[9 13 17 20] Without exception, the data in table 3 show a slower response of $T_{rectal}$ than $T_{intestinal}$ to changes in exercise intensity; however, differences between the two sites do not always reach statistical significance.

### $T_{oesophageal}$ versus $T_{rectal}$ and $T_{intestinal}$

Six of the 12 studies in table 1 simultaneously measured $T_{oesophageal}$, $T_{rectal}$ and $T_{intestinal}$.[9 13 16 17 20] This allows for a comparison of the agreement between $T_{oesophageal}$ and $T_{intestinal}$ in the context of the agreement between $T_{oesophageal}$ and $T_{rectal}$. Only two study datasets were available for comparison of LoA.[13 17] The data of Kolka *et al*[13] showed a statistically significant bias in the comparison of $T_{oesophageal}$ versus $T_{rectal}$ (ie, −0.21℃ (0.33)℃), indicating that $T_{rectal}$ was consistently higher than $T_{oesophageal}$. Furthermore, statistically significant negative heteroscedasticity was evident, indicating that the absolute difference between sites decreased as $T_c$ increased. Conversely, no statistically significant bias (−0.02℃ (0.43)℃) or statistically significant heteroscedasticity was

**Table 3** A comparison of the time course and rate of core temperature change at the onset or cessation of exercise when measured at oesophageal, intestinal and rectal sites

| | Oesophageal | Intestinal | Rectal |
|---|---|---|---|
| Time for 0.1℃ change from start of exercise (min) | | | |
| Kolka *et al,*[13] 40% $Vo_{2peak}$ | 4.4 (2.7)* | 7.5 (4.8)† | 12.3 (3) |
| Kolka *et al,*[13] 80% $Vo_{2peak}$ | 1.8 (0.8)* | 3.8 (1.5)† | >5.0 (0) |
| Lee *et al,*[17] 40% $Vo_{2peak}$ | 10 (1.1) | 14 (1.2) | 15.7 (1.6)‡ |
| Rate of change during exercise (℃/min) | | | |
| Kolka *et al,*[14] 40% $Vo_{2peak}$ | 0.050 (0.013)* | 0.031 (0.014) | 0.018 (0.005) |
| Kolka *et al,*[14] 80% $Vo_{2peak}$ | 0.112 (0.028)* | 0.066 (0.035)† | 0.018 (0.009) |
| Lee *et al,*[17] 40% $Vo_{2peak}$ | 0.022 (0.005) | 0.021 (0.004) | 0.016 (0.004) |
| Time to steady-state temperature during exercise (min) | | | |
| Kolka *et al,*[13] 40% $Vo_{2peak}$ | 18.0 (6.1) | 25.2 (9.1)† | 37.3 (4.6)‡ |
| Time for 0.1℃ change from end of exercise (min) | | | |
| Kolka *et al,*[13] from 40% $Vo_{2peak}$ | 2.3 (0.5)* | 6.5 (3.1)† | 12.2 (3.3) |
| Lee *et al,*[17] from 65% $Vo_{2peak}$ | 3.7 (0.4) | 7.1 (1.5) | 10.6 (1.9)‡ |
| Rate of change during recovery (℃/min) | | | |
| Lee *et al,*[17] from 65% $Vo_{2peak}$ | −0.030 (0.002)* | −0.023 (0.003)† | −0.010 (0.003) |

Values are mean (SD).
*$T_{oesophageal}$ significantly different from $T_{intestinal}$ and $T_{rectal}$, $p<0.05$.
†$T_{intestinal}$ significantly different from $T_{rectal}$ $p<0.05$.
‡$T_{rectal}$ significantly different from $T_{oesophageal}$, $p<0.05$.

evident in the comparison of $T_{oesophageal}$ versus $T_{intestinal}$. On the other hand, the data of Lee *et al*[17] show similar non-significant bias and 95% LoA for $T_{oesophageal}$–$T_{rectal}$ and $T_{oesophageal}$–$T_{intestinal}$ comparisons. Although limited to two datasets, the analysis suggests that the agreement between $T_{oesophageal}$ and $T_{intestinal}$ is as good as, if not better than, the agreement between $T_{oesophageal}$ and $T_{rectal}$. Support for this conclusion is provided by O'Brien *et al*,[16] who reported that the RMSD between $T_{oesophageal}$ and $T_{intestinal}$ was significantly less ($p<0.05$) than the RMSD between $T_{rectal}$ and $T_{oesophageal}$ during one of their four experimental conditions (ie, 3 h of resting cold-water immersion) and not statistically different in the remaining experimental conditions.

### Responsiveness of $T_{oesophageal}$ versus $T_{intestinal}$ and $T_{rectal}$

Table 3 shows that the intestinal site is intermediate to oesophageal and rectal sites in responding to a change in $T_c$ at the onset or cessation of exercise or in response to changes in exercise intensity, reinforcing earlier observations.[9 20] For this reason, during dynamic non-steady-state $T_c$ situations, $T_{intestinal}$ may agree more closely with $T_{oesophageal}$ than does $T_{rectal}$. This is clearly shown in fig 1, where $T_{rectal}$ was significantly lower ($p<0.05$) than $T_{oesophageal}$ after 20 min of exercise at 40% $Vo_{2peak}$ and after a further 20 min at 65% $Vo_{2peak}$, whereas $T_{intestinal}$ was not significantly ($p>0.05$) different from $T_{oesophageal}$ at these time points.

## Reliability

Only one study from table 1 has directly assessed the reliability of ingestible temperature sensors.[19] In that study, nine men performed two 90 min bouts of shuttle running separated by 7 days, with LoA analysis showing no significant bias (ie, −0.01℃ (0.23℃); $p>0.05$) and 95% LoA of −0.24℃ to +0.22℃ between the two bouts, indicating an acceptable level of reliability.[19]

## Factors affecting agreement

Table 1 shows that a number of key variables (eg, sensor calibration, timing of ingestion) have differed markedly across validation studies. These variables can potentially affect the validity and reliability of $T_{intestinal}$ and a consideration of their effect will also inform practical application.

### Calibration

The precision and accuracy of the manufacturer's calibration can be confirmed by the investigator before use by comparing sensor temperature against a calibrated thermometer across a physiologically valid range of water bath temperatures. For example, Lee *et al*[17] developed individual linear regression equations for each of their seven sensors by comparing sensor and calibrated mercury thermometer temperature at water bath temperatures of 30℃, 34℃, 38℃, and 42℃. Although the composite of 28 comparisons showed a highly linear relationship (ie, $R^2 = 0.999$; ℃ = 0.997(sensor temperature) + 0.245), sensor temperatures were found to be significantly ($p<0.05$) and consistently lower than the calibrated thermometer across the range of temperatures. Sparling *et al*[14] highlighted that of the six sensors used in their study, three sensors measured lower (ie, 0.05℃, 0.1℃ and 0.1℃) and three sensors measured higher (ie, 0.25℃, 0.25℃ and 0.6℃) than a calibrated thermometer. Therefore, it is essential that each sensor is individually calibrated before use. Four studies in table 1 clearly stated their calibration procedures,[14–17] three studies stated that calibration was undertaken but did not elaborate on their procedures,[9 11 19 20] whereas five studies did not state whether calibration was undertaken.[12 13 18 21]

**Table 4** Field-based sport and occupational applications of the ingestible telemetric temperature sensor

| Reference | Application | Characteristics | Sample | Environment | Data collection |
|---|---|---|---|---|---|
| White *et al*[24] | Dry-suit scuba diving: open water search and rescue activity | Duration, 34–189 min<br>Depth, NS | 20 M | Ice, W = 2.8˚C<br>DB, 0.6˚C<br>Warm: W = 21˚C<br>DB = 23˚C | Continuous |
| Leclerc *et al*[25] | Open-water swimming | Distance, 40 km<br>Duration, F = 666 (36) min, M = 628 (40) min | 17<br>(4 F, 13 M) | W = 18.3–22.4˚C<br>DB = 23˚C | Intermittent |
| Mekjavic *et al*[26] | Thermal suit saturation diving | Duration = 31–450 min<br>Depth = 54–160 m | 30 M | W = 4–6˚C | Continuous |
| Fowkes Godek *et al*[27] | American football and cross-country running | Football, pre-season twice per day practice<br>Runners, pre-season twice per day steady running | 15 M<br>(10 football, 5 run) | DB = 26.1–35˚C<br>RH = 36–71% | Intermittent |
| Byrne *et al*[28] | Distance running | Distance = 21 km<br>Duration = 118 (13) min | 18 M | DB = 26.3–30.6˚C<br>RH = 75–90% | Continuous |
| Castellani *et al*[29] | Military field training | Duration = 54 h<br>Varied physical and cognitive challenges, sleep deprivation, negative energy balance | 26<br>(12 F, 14 M) | DB = 3.6–21.4˚C<br>RH = 72 (21)%<br>V = 1.6 (0.7) m/s | Continuous |
| Edwards and Clark[30] | Soccer | Duration, 90 min<br>Amateur and professional match play | 15 M<br>(8 amateur, 7 professional) | Amateur<br>DB = 16˚C<br>RH = 47%<br>Professional<br>DB = 19˚C<br>RH = 53% | Intermittent |
| Fowkes Godek *et al*[31] | American football | Twice per day practice | 14 M<br>(8 linemen, 6 backs) | DB = 19.4–29.2˚C | Intermittent |
| Laursen *et al*[32] | Ironman triathlon | Distance = 226 km<br>Duration = 611 (49) min<br>Swim = 3.8 km, cycle = 180 km, run = 42.2 km | 9 M | DB = 19–26˚C<br>RH = 44–87% | Intermittent |

DB, dry bulb air temperature; F, female; M, male; RH, relative humidity; V, wind velocity; W, water temperature.
Values are mean (SD) or range.

## Gastrointestinal motility

The absence of a fixed anatomical position for temperature measurement presents a number of potential problems when using the ingestible sensor, such as the possibility of temperature gradients along the gastrointestinal tract, the acute modifying effects of fluid and food ingestion on $T_{intestinal}$, and the uncertainty of sensor transit time.

### *Gastrointestinal temperature gradients*

Table 2 provides evidence of significant ($p<0.05$) differences between $T_{intestinal}$ and $T_{rectal}$, indicating a temperature gradient along the gastrointestinal tract. Kolka *et al*[13] hypothesised that movement of the sensor from the stomach to the small intestine was responsible for temperature variations of 0.2–0.3℃ observed in two of their eight subjects. When data collection commenced soon after sensor ingestion, Livingstone *et al*[12] observed a variable $T_{intestinal}$–$T_{rectal}$ relationship, which they hypothesised was due to movement of the sensor through the stomach and upper intestine. They observed a more stable and close relationship when the sensor was allowed time (amount not stated) to traverse the gastrointestinal tract.[12] O'Brien *et al*[16] had volunteers ingest sensors 12 h before data collection and suggested that this time period should overcome the potential temperature fluctuations associated with sensor transit through the stomach. On the other hand, in a 36 h experiment in which sensor ingestion occurred 40 min before data collection, Ducharme *et al*.[21] reported that $T_{rectal}-T_{intestinal}$ differences were similar in the first hour (0.15℃ (0.11)℃) and in the 36th hour (0.15℃ (0.14)℃) of data collection, suggesting no effect of sensor transit on the $T_{rectal}$–$T_{intestinal}$ relationship. Sparling *et al*[14] reported no effect on the $T_{rectal}$–$T_{intestinal}$ relationship when ingestion occurred 3–4 vs 8–9 h before data collection; however, the comparison was based on only three subjects in each group. Observations in resting animals suggest that the gastrointesinal tract is a major source of heat, exhibiting temperatures significantly higher ($p<0.05$) than aortic blood.[33 34] Furthermore, temperature gradients along the gastrointestinal tract were evident, with the duodenum and ileum exhibiting significantly higher ($p<0.05$) temperatures than the stomach, large intestine and rectum.[34] These findings are in line with the observations of the latter three studies in table 2,[17–19] showing significantly higher $T_{intestinal}$ versus $T_{rectal}$ and significantly higher $T_{intestinal}$ versus $T_{oesophageal}$.[17] This indirect evidence suggests the existence of a temperature gradient along the gastrointestinal tract (ie, from stomach/small intestine/large intestine to rectum), and from the gastrointestinal tract to central blood in humans; however, the magnitude of the gradient does not seem to be affected by movement of the ingestible sensor along the gastrointestinal tract.[14 21] Further study is required to determine the magnitude and physiological significance of this temperature gradient.[16]

### *Modifying effects of fluid and food*

If the sensor is located in the stomach, its temperature will be influenced by the temperature of ingested fluid and food. Fox *et al*[20] stated that observing the effect of a small drink of cold fluid clearly establishes whether the sensor has departed the stomach. If the sensor is ingested in the acute period before data collection and fluid/food is to be ingested, then providing fluid/food at a temperature equivalent to $T_c$ (about 37℃) will minimise this effect. This approach was adopted by Ducharme *et al*,[21] who provided fluid at 37℃ throughout their 36 h experiment.

### *Transit time*

Sensor ingestion many hours before data collection (eg, 8–12 h) may ensure departure from the stomach and a more stable $T_c$; however, there is a risk that the sensor may be expelled before data collection. Indeed, O'Brien *et al*[16] reported a loss of sensor on 3 of 36 (8%) occasions after ingestion at 20:00 h for an experiment at 07:00 h the next day. Kolka *et al*[13] reported mean (SD) transit times for eight men as 30.4 (8.9) h, and McKenzie and Osgood[11] reported transit times for six men and four women as 40.8 (26.4) and 62.3 (49.2) h, respectively. Minimum transit times have been reported as 8 h[17] and 12.4 h,[11] with the maximum reported transit time being 5.6 days.[11] McKenzie and Osgood[11] noted that the shortest transit times were associated with sensor ingestion just before the evening meal. In line with this observation, ingesting the sensor with a light meal has been used in a number of studies in an attempt to promote sensor transit from the stomach.[13 15 17] Lee *et al*[17] proposed a sensor ingestion time of 6 h before data collection, which would seem optimal in avoiding both temperature fluctuations in the upper gastrointestinal tract and sensor expulsion before data collection.

## Electromagnetic interference

Reception of the temperature-dependant low-frequency radio wave transmitted from the ingestible sensor is susceptible to electromagnetic interference and can result in erroneous or lost data. Mittal *et al*[35] reported a loss of temperature readings when sensors were subjected to interference from an electromagnetic heating device, but accurate readings were obtained immediately after the device was switched off. Interference from computer screens and laboratory equipment monitors can also prevent accurate data recording.[17] Sources of interference are more likely to be identified and controlled in a laboratory compared with a field-based situation where sources are likely to be unpredictable and beyond the researcher's control.

# APPLICATIONS OF THE INGESTIBLE TEMPERATURE SENSOR

The earliest application of the ingestible temperature sensor can be traced to the study of Adams *et al*,[36] where it was used as a rectal suppository to measure $T_{rectal}$ during prolonged running in the laboratory and after an outdoor marathon race. Keatinge *et al*[37 38] used the sensor as a rectal suppository and also in its intended ingestible form during case studies of sea swimming in the cold waters of the Bering Strait (water temperature = 7.2–7.4℃) and Beagle Channel (water temperature = 8.3–9℃). An advantage of the ingestible sensor is its ability to obtain $T_c$ measurements on large groups of subjects simultaneously, such as a sample of athletes participating in the same event. For example, Byrne *et al*[28] were able to continuously record $T_c$ simultaneously in 18 runners competing in a 21 km road-running race. This contrasts with the difficulty faced by Maron *et al*,[39] who made serial $T_{rectal}$ measurements (approximately every 9 min) in two runners during a 42.2 km marathon by pulling alongside the runners in a moving vehicle and connecting their indwelling rectal probe to a measurement device. Although portable data recorders worn by subjects to continuously record $T_{rectal}$ have been described and applied successfully in freely exercising subjects,[40] issues regarding the invasive, obtrusive and objectionable nature of rectal thermometry remain unresolved.

We are aware of nine published field-based studies using ingestible temperature sensors in subjects undertaking sporting or occupational physical activity.[24–32] Table 4 illustrates these studies and indicates the increasing use of the technology with five of the nine studies published in 2006.[28–32] Six field-based studies have used ingestible sensors to measure $T_c$ during diverse sporting activities.[25 27 28 30–32] The studies provide unique and ecologically valid $T_c$ data and show the efficacy of the method, as all data were obtained during training sessions[27 31] or actual competitive events.[28 30 32] Additionally, three studies

have used ingestible temperature sensors to investigate potential hypothermia and hyperthermia during occupational activity,[24 26 29] such as saturation diving in sea-water depths up to 160 m[26] and during 54 h of sustained Marine Corps cold weather training exercises.[29] The utility of the technology is readily shown in providing, in some cases, continuous $T_c$ data in logistically challenging scenarios and often in extreme environments.

### Data collection problems

Several of the studies in table 4 have reported incidences of poor reliability during sport and occupational applications of the technology. White *et al*[24] reported incomplete or inaccurate data recordings in 7 of 27 (26%) attempts at continuous monitoring of $T_c$ during dry-suit scuba diving. The authors identified a malfunctioning temperature sensor on one occasion, but the causes of the remaining six failures could not be identified. Similarly, Byrne *et al*[28] could not identify the causes responsible for incomplete data recordings in 4 of 22 (18%) attempts at continuous monitoring of $T_c$ in runners undertaking a half-marathon. Laursen *et al*[32] obtained $T_c$ readings intermittently during an Ironman triathlon and was successful on 55 of 72 attempts (24% data loss). The authors suggested that human error when running alongside the athletes and/or electromagnetic interference from external radio waves could potentially account for the lost data.[32] McKenzie and Osgood[11] reported the percentage of missing data points as 6.5% (5.9%) during data collection at minute intervals over 48.6 (35.5) h in 10 subjects. The missing data points were attributed to the sensor and receiver going out of range, such as when sleeping or showering.[11] In summary, field-based use of ingestible sensors have been associated with up to a quarter of the data being incomplete or inaccurate. The principal causes seem to be electromagnetic interference, limitations in sensor transmitting range (ie, VitalSense range = 1 m; CorTemp range = 0.61 m), or experimenter error. However, the potential for data loss must be placed in the context of the objectionable nature of oesophageal or rectal thermometry, where considerable problems with volunteer recruitment and/or drop-out are likely to be experienced by researchers. Indeed, in a study by one of the authors of this review, an entire cohort of volunteers withdrew from the study after their initial exposure to rectal thermometry.[41]

## CONCLUSIONS AND RECOMMENDATIONS

A quantitative review suggests that the agreement between $T_{intestinal}$ and $T_{oesophageal}$ can meet our criteria for acceptance as a valid measure of $T_c$ (ie, bias $<0.1$℃ and 95% LoA within $\pm 0.4$℃). The agreement between $T_{intestinal}$ and $T_{rectal}$ shows a significant systematic bias $>0.1$℃, although the 95% LoA is acceptable. Intestinal sensor temperature responds less rapidly than $T_{oesophageal}$ at the start or cessation of exercise or to a change in exercise intensity, but more rapidly than $T_{rectal}$. Before use, ingestible sensors should be individually calibrated against a certified thermometer across a physiologically valid range of water-bath temperatures, enabling the generation of individual regression formula and the correction of raw data. Ingestion of the sensor 6 h before data collection seems optimal to ensure sensor transit beyond the stomach but not expulsion before data collection. Successful data collection by telemetry is susceptible to electromagnetic interference and is limited by the sensor transmission range (ie, $<1$ m). The ingestible telemetric temperature sensor represents a valid index of $T_c$ that is convenient and shows excellent utility for ambulatory field-based applications. Benefits of the system over indwelling hard-wired probes were recognised and summarised 45 years ago by their early pioneers: ''The radio pill has the great merit that, once swallowed, the subject is unaware of its presence or of measurements being made. It should prove valuable in field studies, in investigations requiring frequent measurements over long periods, or if the subject needs to be entirely free during the observations.''[20]

### What is already known on this topic

- Ingestible telemetric temperature sensors represent an alternative to oesophageal and rectal temperatures as an index of core temperature during exercise.
- Variable relationships between these three indices have been observed in validation studies using small sample sizes, varied protocols and varied statistical methods of comparison.
- The ingestible sensor method is gaining widespread use, particularly in field-based studies.

### What this study adds

- Our quantitative review based on Bland and Altman's limits of agreement suggests the agreement between ingestible sensor and oesophageal temperature can potentially be within our delimitation of acceptable agreement (ie, systematic bias $<0.1$℃ and 95% limits of agreement within $\pm 0.4$℃). The agreement with rectal temperature shows a significant systematic bias $>0.1$℃, with acceptable 95% limits of agreement.
- A review of ingestible sensor applications shows excellent utility for ambulatory field-based uses.


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