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Hearing Devices, Systems, and Methods for Measuring a Core Body Temperature of a User

Abstract

An exemplary hearing device may be configured to be inserted at least partially within an ear canal of a user of the hearing device. The hearing device may include a first temperature sensor configured to detect ear canal temperature within the ear canal, a second temperature sensor configured to detect ambient temperature outside of the ear canal, and a processor. The processor may be configured to determine a work status of the user indicative of an activity level of the user and determine a core body temperature of the user based on the ear canal temperature detected by the first temperature sensor, the ambient temperature detected by the second temperature sensor, and the work status of the user.

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Background/Summary

BACKGROUND INFORMATION

[0001] Hearing devices (e.g., hearing aids) are used to improve the hearing capability and/or communication capability of users of the hearing devices. Such hearing devices are configured to process a received input sound signal (e.g., ambient sound) and provide the processed input sound signal to the user (e.g., by way of a receiver (e.g., a speaker) placed in the user's ear canal or at any other suitable location).

[0002] In addition to being used to facilitate providing the processed input sound signal to the user, hearing devices may include one or more sensors configured to monitor biological attributes of the user while the hearing devices are worn by the user. For example, a behind-the-ear (“BTE”) component of a hearing device may include a skin temperature sensor configured to monitor skin temperature of the user while the BTE component is worn behind the user's ear. However, skin temperature may significantly be affected by external influencing factors such as environmental conditions including ambient temperature, humidity, air velocity, etc. In view of this, a skin temperature sensor alone is inadequate for measuring a core body temperature of a user and often results in underestimated core body temperatures. Accordingly, there remains room to improve the manner in which hearing devices may be used to measure a core body temperature of a user.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] The accompanying drawings illustrate various embodiments and are a part of the specification. The illustrated embodiments are merely examples and do not limit the scope of the disclosure. Throughout the drawings, identical or similar reference numbers designate identical or similar elements.

[0004] FIG. **1** illustrates an exemplary core body temperature processing system that may be implemented according to principles described herein.

[0005] FIG. **2** illustrates an exemplary implementation of the core body temperature processing system of FIG. **1** according to principles described herein.

[0006] FIG. **3** illustrates an exemplary flow diagram that may be implemented according to principles described herein.

[0007] FIGS. **4-5** illustrate exemplary configurations of hearing devices that may be implemented according to principles described herein.

[0008] FIGS. **6-7** illustrate exemplary configurations of hollow core optical waveguides that may be included in hearing devices according to principles described herein.

[0009] FIG. **8** illustrates an exemplary method according to principles described herein.

[0010] FIG. **9** illustrates an exemplary computing device according to principles described herein.

DETAILED DESCRIPTION

[0011] Hearing devices, systems, and methods for measuring a core body temperature of a user are described herein. As will be described in more detail below, an exemplary hearing device may be configured to be inserted at least partially within an ear canal of a user of the hearing device and may comprise a first temperature sensor configured to detect ear canal temperature within the ear canal, a second temperature sensor configured to detect ambient temperature outside of the ear canal, and a processor. The processor may be configured to determine a work status of the user indicative of an activity level of the user and determine a core body temperature of the user based on the ear canal temperature detected by the first temperature sensor, the ambient temperature detected by the second temperature sensor, and the work status of the user.

[0012] By using hearing devices, systems and methods such as those described herein, it is possible to provide a non-invasive solution for an accurate determination of core body temperatures. For example, hearing devices such as those described herein may be configured with multiple temperature sensors that provide temperature readings that, in combination with other measured parameters (e.g., heart rate, work status, etc.), may be used to determine an accurate measure of a core body temperature of a user of the hearing devices. Moreover, hearing devices, systems, and methods such as those described herein may beneficially be configured to facilitate tracking and/or monitoring various conditions (e.g., fever, insomnia, fatigue, infection, etc.) that may be associated with a core body temperature of a user. In addition, hearing devices, systems and methods such as those described herein may provide one or more graphical user interface views that provide a user with information associated with physiological and/or pathological conditions associated with core body temperature. Other benefits of the systems and methods described herein will be made apparent herein.

[0013] FIG. **1** illustrates an exemplary core body temperature processing system **100** ("system **100**") that may be implemented according to principles described herein. As shown, system **100** may include, without limitation, a memory **102** and a processor **104** selectively and communicatively coupled to one another. Memory **102** and processor **104** may each include or be implemented by hardware and/or software components (e.g., processors, memories, communication interfaces, instructions stored in memory for execution by the processors, etc.). In some examples, memory **102** and/or processor **104** may be implemented by any suitable computing device such as described herein. In other examples, memory **102** and/or processor **104** may be distributed between multiple devices and/or multiple locations as may serve a particular implementation. Illustrative implementations of system **100** are described herein.

[0014] Memory **102** may maintain (e.g., store) executable data used by processor **104** to perform any of the operations described herein. For example, memory **102** may store instructions **106** that may be executed by processor **104** to perform any of the operations described herein. Instructions **106** may be implemented by any suitable application, software, code, and/or other executable data instance.

[0015] Memory **102** may also maintain any data received, generated, managed, used, and/or transmitted by processor **104**. Memory **102** may store any other suitable data as may serve a particular implementation. For example, memory **102** may store hearing loss profile data, user preference data, setting data, ambient temperature data, ear canal temperature data, heart rate data, work status information, machine learning data, graphical user interface content, and/or any other suitable data.

[0016] Processor **104** may be configured to perform (e.g., execute instructions **106** stored in memory **102** to perform) various processing operations associated with measuring a core body temperature of a user. For example, processor **104** may perform one or more operations described herein to determine a core body temperature of a user based on ear canal temperature detected by a first temperature sensor, ambient temperature detected by a second temperature sensor, and a work status of the user. These and other operations that may be performed by processor **104** are described herein.

[0017] As used herein, a "hearing device" may be implemented by any device or combination of devices configured to provide or enhance hearing to a user. For example, a hearing device may be implemented by a hearing aid configured to amplify audio content to a recipient, a sound processor included in a cochlear implant system configured to apply electrical stimulation representative of audio content to a recipient, a sound processor included in a stimulation system configured to apply electrical and acoustic stimulation to a recipient, or any other suitable hearing prosthesis. In some examples, a hearing device may be implemented by BTE housing configured to be worn behind an ear of a user. In some examples, a hearing device may be implemented by an in-the-ear ("ITE") component configured to at least partially be inserted within an ear canal of a user. In some examples, a hearing device may include a combination of an ITE component, a BTE housing, and/or any other suitable component.

[0018] In certain examples, hearing devices such as those described herein may be implemented as part of a binaural hearing system. Such a binaural hearing system may include a first hearing device associated with a first ear of a user and a second hearing device associated with a second ear of a user. In such examples, the hearing devices may each be implemented by any type of hearing device configured to provide or enhance hearing to a user of a binaural hearing system. In some examples, the hearing devices in a binaural system may be of the same type. For example, the hearing devices may each be hearing aid devices. In certain alternative examples, the hearing devices may be of a different type. For example, a first hearing device may be a hearing aid and a second hearing device may be a sound processor included in a cochlear implant system.

[0019] In some examples, a hearing device may additionally or alternatively be implemented by one or more earbuds, one or more headphones, one or more hearables (e.g., smart headphones), and/or any other suitable device that may be used to facilitate a user perceiving sound. In such examples, the user may correspond to either a hearing impaired user or a non-hearing impaired user.

[0020] System **100** may be implemented in any suitable manner. For example, system **100** may be implemented by a hearing device and/or a computing device that is communicatively coupled in any suitable manner to the hearing device. To illustrate an example, FIG. **2** shows an exemplary implementation **200** in which system **100** may be provided in certain implementations. As shown in FIG. **2**, implementation **200** includes a hearing device **202** that is associated with a user **204** and that is communicatively coupled to a computing device **206** by way of a network **208**. User **204** may correspond to any individual that is a user of a hearing device such as described herein.

[0021] Hearing device **202** may correspond to any suitable type of hearing device such as described herein. Hearing device **202** may include, without limitation, a memory **210** and a processor **212** selectively and communicatively coupled to one another. Hearing device **202** may also include a housing configured to be inserted at least partially within an ear canal of a user of the hearing device. Such a housing may be configured in any suitable manner. For example, in certain implementations, the housing may form a portion of an ITE component that is at least partially inserted within an ear canal of a user. In certain examples, the housing may be custom formed for a particular user. Such customized housings may provide a more stable core body temperature measurement compared to standard housings under different environmental conditions. This may be achieved by customized housings creating a tight seal of the ear canal resulting in an increased thermal coupling to a wall of the ear canal and a decreased coupling to the environment. This in turn may mitigate the influence of environmental factors such as ambient temperature, humidity, solar irradiance, and/or air velocity in temperature readings from the ear canal. In addition, customized housings may minimize the effect that physical activity may have by reducing the amount of air exchange between the ear canal and the surrounding environment. In certain alternative examples, the housing may correspond to a standard housing that is configured to universally fit multiple different users. Exemplary housings are described herein.

[0022] Memory **210** and processor **212** may each include or be implemented by hardware and/or software components (e.g., processors, memories, communication interfaces, instructions stored in memory for execution by the processors, etc.). In some examples, memory **210** and processor **212** may be housed within or form part of a BTE housing. In some examples, memory **210** and processor **212** may be located separately from a BTE housing (e.g., in an ITE component). In some alternative examples, memory **210** and processor **212** may be distributed between multiple devices (e.g., multiple hearing devices in a binaural hearing system) and/or multiple locations as may serve a particular implementation.

[0023] Memory **210** may maintain (e.g., store) executable data used by processor **212** to perform any of the operations associated with hearing device **202**. For example, memory **210** may store instructions **214** that may be executed by processor **212** to perform any of the operations associated with hearing device **202** assisting a user in hearing. Instructions **214** may be implemented by any suitable application, software, code, and/or other executable data instance.

[0024] Memory **210** may also maintain any data received, generated, managed, used, and/or transmitted by processor **212**. For example, memory **210** may maintain any suitable data associated with a hearing loss profile of a user, ambient temperature data, ear canal temperature data, health profile information, etc. Memory **210** may maintain additional or alternative data in other implementations.

[0025] Processor **212** is configured to perform any suitable processing operation that may be associated with hearing device **202**. For example, when hearing device **202** is implemented by a hearing aid device, such processing operations may include monitoring ambient sound and/or representing sound to user **204** via an in-ear receiver. Processor **212** may be implemented by any suitable combination of hardware and software.

[0026] As shown in FIG. **2**, hearing device **202** further includes temperature sensors **216** (e.g., temperature sensors **216-1** and **216-2**). Temperature sensor **216-1** may be configured to detect ear canal temperature within an ear canal of user **204**. Temperature sensor **216-1** may be provided in a housing of hearing device **202** that is configured to be inserted at least partially in the ear canal of user **204**. Temperature sensor **216-1** may be configured to detect the ear canal temperature at skin of the ear canal (e.g., at the ear canal wall). Temperature sensor **216-1** may also be configured to detect the ear canal temperature at a location within the ear canal remote from the skin. Assuming thermal equilibrium within the ear canal, the temperature measured at the skin may substantially correspond to the temperature measured remote from the skin. The ear canal temperature may thus also be denoted as a skin temperature within the ear canal. Ear canal temperature data indicative of the ear canal temperature provided by temperature sensor **216-1** may be accessed by processor **104**, **212**. Temperature sensor **216-1** may include any suitable type of temperature sensor as may serve a particular implementation. For example, temperature sensor **216-1** may include a flow temperature sensor, an infrared (“IR”) thermometer, and/or a contact temperature sensor. Temperature sensor **216-2** may be configured to detect ambient temperature outside of an ear canal of a user. Temperature sensor **216-2** may be positioned in any suitable manner with respect to hearing device **202** to detect ambient temperature. For example, temperature sensor **216-2** may be provided on a BTE component. Alternatively, temperature sensor **216-2** may be provided on a faceplate of an ITE component. Ambient temperature data indicative of the ambient temperature provided by temperature sensor **216-2** may be accessed by processor **104**, **212**. Temperature sensor **216-2** may include any suitable type of temperature sensor as may serve a particular implementation. Exemplary configurations of temperature sensors are described herein.

[0027] In certain examples, hearing device **202** may further include a motion sensor **218**. Motion sensor **218** may be implemented by any suitable type of motion sensor as may serve a particular implementation. For example, motion sensor **218** may include an accelerometer and/or a gyroscope in certain examples. In some examples, motion sensor **218** may be implemented as an inertial measurement unit (IMU). Motion sensor **218** may be configured to detect motion data that may be used by system **100** to determine a work status of user **204**. In certain examples, hearing device **202** may further include a heart rate sensor **220**. Heart rate sensor **220** may be implemented by any suitable type of heart rate sensor as may serve a particular implementation. For example, heart rate sensor **220** may comprise a photoplethysmography (PPG) sensor and/or an electrocardiography (ECG) sensor in certain examples. Heart rate sensor **220** may be configured to detect heart rate data indicative of a heart rate of the user.

[0028] Motion sensor **218** and heart rate sensor **220** are shown in dashed lines in FIG. **2** because, in certain examples, a motion sensor and/or a heart rate sensor may be included in a device other than hearing device **202**. For example, computing device **206** may correspond to a smartphone or a smartwatch with a motion sensor and/or a heart rate sensor. In such examples, hearing device **202** may access or otherwise obtain motion data from the smartphone or smartwatch to facilitate measuring the core body temperature of user **204**. In some examples, the heart rate may be determined based on the ear canal temperature, the ambient temperature, and data including the motion data, e.g., the work status determined therefrom. In those examples, heart rate sensor **220** may not be required. In some examples, the heart rate may be determined based on the ear canal temperature, the ambient temperature, and data including the motion data and the heart rate data.

[0029] Computing device **206** may include or be implemented by any suitable hardware and/or software components (e.g., processors, memories, communication interfaces, instructions stored in memory for execution by the processors, etc.) and may include any combination of computing devices as may serve a particular implementation. In certain examples, computing device **206** may correspond to a smart charging device for hearing device **202**, a laptop computer, a desktop computer, a tablet computer, and/or any other suitable computing device that may be configured to facilitate measuring a core body temperature of a user. In such examples, computing device **206** may be configured to perform any suitable operations such as those described herein to process temperature information, biological information, work status information, etc. to facilitate measuring a core body temperature of a user.

[0030] Network **208** may include, but is not limited to, one or more wireless networks (Wi-Fi networks), wireless communication networks, mobile telephone networks (e.g., cellular telephone networks), mobile phone data networks, broadband networks, narrowband networks, the Internet, local area networks, wide area networks, and any other networks capable of carrying data and/or communications signals between hearing device **202** and computing device **206**. In certain examples, network **208** may be implemented by a Bluetooth protocol (e.g., Bluetooth Classic, Bluetooth Low Energy (“LE”), etc.) and/or any other suitable communication protocol to facilitate communications between hearing device **202** and computing device **206**. Communications between hearing device **202**, computing device **206**, and any other device/system may be transported using any one of the above-listed networks, or any combination or sub-combination of the above-listed networks.

[0031] System **100** may be implemented by computing device **206** or hearing device **202**. Alternatively, system **100** may be distributed across computing device **206** and hearing device **202**, or distributed across computing device **206**, hearing device **202**, and/or any other suitable computing system/device.

[0032] Core body temperature is an important indicator of various medical conditions that a user of a hearing device may experience. For example, the core body temperature of a user may be indicative of fever, insomnia, infection, metabolic functionality, and/or depression. Typically, body temperature sensors implemented in wearable devices are configured to detect ear canal temperature. Even though ear canal temperature may provide relevant information for estimating a core body temperature, the use of single ear canal temperature measurements alone is insufficient and often results in underestimated or overestimated core body temperatures. This is because ear canal temperature may be significantly affected by external influencing factors such as environmental conditions including ambient temperature, humidity, and/or air velocity. Other techniques for measuring temperature (e.g., rectal, gastrointestinal, etc.) may provide relatively more accurate core body temperature measurements than ear canal temperature measurements but are invasive and inappropriate for wearable devices outside of a laboratory environment.

[0033] Hearing devices such as those described herein possess technical advantages for temperature monitoring due to the shared vasculature between the ear canal and the hypothalamus (the body's temperature control center) originating from the internal carotid artery. To that end, system **100** (e.g., processor **104**, processor **212**, etc.) may be configured to leverage information obtained by way of hearing devices such as those described herein to facilitate measuring the core body temperature of a user. This may be accomplished in any suitable manner. To illustrate, FIG. **3** shows a flow diagram **300** with various operations that may be performed by system **100** in measuring a core body temperature of a user. As shown in FIG. **3**, at operation **302**, system **100** may access ear canal temperature of a user. This may be accomplished in any suitable manner. For example, system **100** may obtain ear canal temperature data from temperature sensor **216-1**.

[0034] At operation **304**, system **100** may access ambient temperature in an environment of a user. This may be accomplished in any suitable manner. For example, system **100** may obtain ambient temperature data from temperature sensor **216-2**.

[0035] At operation **306**, system **100** may determine a work status of a user that is indicative of an activity level of the user. In certain examples, the work status may indicate whether the user is in a resting state or a physically active state. System **100** may determine the work status in any suitable manner. For example, system **100** may access information detected by a motion sensor (e.g., motion sensor **218**) to determine the work status of the user. To illustrate an example, information received from a motion sensor may indicate that user **204** is currently walking based on a pattern of accelerations detected by the motion sensor. Accordingly, system **100** may determine that user **204** is at a relatively high level of activity. Alternatively, information received from the motion sensor may indicate that user **204** has not moved for a predefined amount of time. Accordingly, system **100** may determine that user **204** is at a relatively low level of activity. In some instances, the activity level and/or work status may be determined from information provided by a physiological sensor, e.g., in place of the motion data provided by motion sensor **218** or in addition to the motion data. For example, in cases where there is a high effort but a low motion signal, e.g., at a particular region of the user's body such as at the head level (e.g., during stationary cycling, high resistance training, leg work, isometric workouts, etc.) physiological sensor data may be gathered to estimate the activity level and/or work status, e.g., additionally or alternatively to the motion data. In some instances, the physiological sensor data may comprise heart rate data. For instance, the heart rate data may be provided by heart rate sensor **220**. To illustrate, the heart rate may be evaluated relative to a heart rate threshold, and when the heart rate exceeds the threshold, the work status may be set to a predetermined value. The heart rate threshold may be set and/or predetermined by taking into account information about the user, e.g., the user's age. The heart rate threshold may also be set and/or predetermined by taking into account averaged heart rates of the user and/or other persons.

[0036] In certain examples, as illustrated in FIG. **3** as an operation **308** shown in dashed lines, system **100** may further determine a heart rate of the user to facilitate determining a core body temperature of a user. In such examples, system **100** may obtain the heart rate in any suitable manner. For example, in certain implementations, hearing device **202** may further include a heart rate sensor that may be configured to measure the heart rate of user **204** while hearing device **202** is worn by user **204**. Alternatively, system **100** may obtain the heart rate from a device that is communicatively coupled to hearing device **202**. For example, a smartwatch communicatively coupled to hearing device **202** may be configured to measure the heart rate of user **204** at any suitable time and provide such information to hearing device **202** to facilitate measuring the core body temperature of user **204**.

[0037] At operation **310**, system **100** may process the ambient temperature, the ear canal temperature, and the work status (and optionally the heart rate) to determine the core body temperature of the user. System **100** may be configured to perform operation **310** in any suitable manner. For example, in certain implementations, system **100** may be configured to use a model, such as a linear regression model or a nonlinear regression model, to estimate the core body temperature of the user. With such a linear regression model, a combination of non-invasive parameters associated with core body temperature may be used by system **100** to improve determining the core body temperature according to the following formula.

$T_c=(a\times HR)^A+(b\times T_e)^B+(c\times T_a)^c+(d\times W)^D+e$

[0038] Where "a," "b," "c," "d," and "e" are unknown coefficients and "A", "B", "C", "D" are unknown exponents that may be determined empirically based on intended conditions and target age groups. In particular, "A", "B", "C", "D" may be selected to be any value larger than zero, e.g., equal to one. "T_e" (>36.5° C.) is the insulated ear canal temperature. "T_a" is the ambient temperature (affecting the ear canal temperature and may therefore also be denoted as "skin microclimate temperature") that may be measured by, for example, temperature sensor **216-2**. "W" is the work status of the user (e.g., at rest=0; during exercise=1). The work status may be determined based on accelerometer data (e.g., captured by motion sensor **218**) indicating whether the user is at rest or performing physical activity. The linear regression model may use the following ranges for HR, T_e, T_a; HR: 40-180 bpm; T_e: from 35-45° C.; and T_a: −10 to 45° C. An example range of the unknown coefficients may be as follows. [0039] a(HR): 0.001 to 0.05 [0040] b(T_e): 0.02 to 0.8 [0041] c(T_a): −0.12 to 0.12 [0042] d(Work): −0.5 to 0.5 [0043] e: 10 to 40

[0044] At operation **312**, system **100** may output the core body temperature. This may be accomplished in any suitable manner. For example, in certain implementations, system **100** may provide an audio notification to user **204** by way of hearing device **202** that informs user **204** of the core body temperature. Additionally or alternatively, system **100** may be configured to output the core body temperature to an external device for presentation to the user. For example, computing device **206** may correspond to a smart phone communicatively coupled to hearing device **202** by way of network **208**. In such an example, system **100** may direct the smart phone to display a graphical user interface with information indicative of the core body temperature of the user.

[0045] In certain examples, system **100** may leverage an additional hearing device to facilitate determining a core body temperature of a user. In such examples, a first hearing device may be provided at a first ear of the user and a second hearing device may be provided at a second ear of the user. In such examples, both the first hearing device and the second hearing device may be configured in a manner similar to hearing device **202**. As such, the first hearing device may be configured to determine a core body temperature value for the user and the second hearing device may be configured to determine an additional core body temperature value for the user. In such examples, system **100** may be configured to determine a core body temperature of the user based on the core body temperature value and the additional core body temperature value. This may be accomplished in any suitable manner. For example, system **100** may empirically and mathematically combine the core body temperature value and the additional core body temperature value into one output value to determine the core body temperature of the user. In certain examples, this may include system **100** determining an average core body temperature based on the core body temperature value and the additional core body temperature value.

[0046] FIG. **4** shows an exemplary configuration **400** that a hearing device may have in certain examples. As shown in FIG. **4**, a hearing device **402** includes a housing **404** and a faceplate **406**. Housing **404** may be customized to fit within an ear canal **408** of a user. For example, housing **404** may be provided as a shell customized to an individual ear canal shape of the user. A first temperature sensor **410** is provided on a surface of housing **404** and is configured to detect ear canal temperature within ear canal **408**. A second temperature sensor **412** is provided on an externally facing surface of faceplate **406** and is configured to detect ambient temperature outside of ear canal **408**. In other examples, the hearing device may include a housing which is adapted for insertion in an ear canal of an average size and/or shape (e.g., a housing that is not customized to an individual ear canal). In such examples, the housing may be provided with a flexible sealing member, e.g., a dome, to provide for a seat of the hearing device inside the ear canal at the ear canal wall. The housing may further comprise an enclosure for accommodating hearing device components, e.g., a receiver, to which the sealing member is attached. The first temperature sensor **410** may be provided, for instance, at or in the enclosure for the hearing device components and/or at the sealing member.

[0047] In certain examples, a temperature sensor that is configured to detect ambient temperature outside of an ear canal may be provided on a BTE component instead of a faceplate. To illustrate, FIG. **5** shows another exemplary configuration **500** that a hearing device may have in alternative examples. As shown in FIG. **5**, configuration **500** includes an ITE component **502** including a housing **504**, a faceplate **506**, and a first temperature sensor **508** that may be configured to detect ear canal temperature within an ear canal of a user. As shown in FIG. **5**, ITE component **502** is communicatively coupled to a BTE component **510** by way of a cable **512**. BTE component **510** includes a second temperature sensor **514** that is configured to detect ambient temperature outside of the ear canal.

[0048] The position of second temperature sensor **514** on BTE component **510** is provided for illustrative purposes only. It is understood that second temperature sensor **514** may be provided at any suitable other position on BTE component **510** as may serve a particular implementation. In addition, in certain examples, BTE component **510** may include a plurality of temperature sensors configured to detect ambient temperature outside of the ear canal.

[0049] In certain examples, a housing of a hearing device may include a hollow core optical waveguide for a temperature sensor that is configured to detect ear canal temperature within an ear canal of a user. In such examples, the temperature sensor may correspond to an IR thermometer. The hollow core optical waveguide may be configured to enhance coupling efficiency of IR radiation from tissue in the ear canal to the IR thermometer while minimizing optical loss. Hollow core optical waveguides facilitate reliable and repeatable readings and detection of small variations in body temperature. In addition, hollow core optical waveguides may facilitate mitigating the influence of environmental factors such as ambient temperature, humidity, wind speed, etc.

[0050] Hollow core optical waveguides such as those described herein may be configured in any suitable manner. In certain implementations, a hollow core optical waveguide may have a funnel shape. To illustrate, FIG. **6** shows an exemplary configuration **600** of an ITE component **602** that includes a housing **604** and a faceplate **606** that includes an ambient temperature sensor **608** provided on an externally facing surface thereof. An IR thermometer **610** is provided internally within housing **604** with a funnel shaped hollow core optical waveguide **612** configured to enhance coupling efficiency of IR radiation from tissue in ear canal **614** to IR thermometer **610**. Funnel shaped hollow core optical waveguide **612** may be configured in any suitable manner such that when IR radiation is coupled from a wide end of waveguide **612** and propagates to a fine end of waveguide **612**, the IR radiation output at the fine end is condensed. Waveguide **612** may have any suitable thickness as may serve a particular implementation. For example, in certain implementations, waveguide **612** may have a thickness of 0.3-0.5 mm.

[0051] In certain alternative implementations, a hollow core optical waveguide may have a tube shape. To illustrate, FIG. **7** shows an exemplary configuration **700** of an ITE component **702** that includes a housing **704** and a faceplate **706** that includes an ambient temperature sensor **708** provided on an externally facing surface thereof. An IR thermometer **710** is provided internally within housing **704** with a tube shaped hollow core optical waveguide **712** configured to facilitate IR radiation propagating from a distal end of tube shaped hollow core optical waveguide **712** near skin of ear canal **714** to a proximal end of tube shaped hollow core optical waveguide **712** where IR thermometer **710** is located. Tube shaped hollow core optical waveguide **712** may have any suitable dimensions as may serve a particular implementation. For example, in certain implementations, tube shaped hollow core optical waveguide **712** may have a core inner diameter of 3 to 4 mm and a thickness of tube shaped hollow core optical waveguide **712** may be 0.3-0.5 mm.

[0052] In certain examples, a hollow core optical wave guide may be covered with a covering to provide ingress protection against earwax. For example, the wide end of a funnel shaped hollow core optical waveguide may be covered with such a covering. The covering may be formed of any suitable material as may serve a particular implementation. For example, the covering may be

formed with a thin lens, glue, lacquer, or any other suitable substance to provide ingress protection against earwax.
[0053] In certain alternative implementations, system **100** may use a hybrid method to facilitate measuring a core body temperature of a user. Such a hybrid method makes use of the fact that the hypothalamus is the body's temperature control center, which regulates temperature by maintaining a fine balance between actual metabolic rate (heat production) and corresponding heat loss (e.g., through radiation, evaporation, convection/conduction). ITE devices/hearables possess technical advantages for temperature monitoring because the shared vasculature between the ear canal and the hypothalamus originating from the carotid artery may be used to accurately estimate a core body temperature of a user. In view of this, the hybrid method may estimate the core body temperature based on the arterial heat balance (ear canal shared vasculature with hypothalamus). A heat balance equation that may be used by system **100** to calculate absolute/relative core body temperature expresses the balance between the metabolic heat from the blood supply and the heat dissipated into the atmosphere to obtain thermal homeostasis.
[0054] The purpose of the thermoregulation system of the human body is to keep its constant core internal temperature, and for long exposures to a constant (moderate) thermal environment with a constant metabolic rate, the heat production is balanced with heat loss, while the heat storage within the human body is not significant. The produced heat is conducted by heat conduction through body tissues and bones and convection in blood vessels. Such heat flows through a series of thermal resistances from arteries as a proxy for core body temperature (the shared vasculature of the ear canal with the hypothalamus as body temperature control center) to the ear skin and from the ear skin to the surrounding environment.
[0055] Heat flow from the core arterial source to the surface of ear canal's skin can be described with the following heat transfer equation (based on electrical analog of heat flow and temperature principle):

$q_1=1/R_1\times(T_c-T_e)$ [0056] where "q.sub.1" is heat flow, "T.sub.e" and "T.sub.c" are the ear canal and core temperatures, respectively, and "R1" is thermal resistance. Heat loss of the ear canal to the environment (e.g., as a result of temperature gradient from the ear canal and ambient temperature) may be calculated with the following equation (based on electrical analog of heat flow and temperature principle):

$q_2=1/R_2\times(T_e-T_a)$ [0057] where "q2" is heat flow, "T.sub.e" and "T.sub.a" are the ear canal and ambient temperatures, respectively, and "R.sub.2" is thermal resistance. At equilibrium the heat flux from the blood supply (q1) and the heat dissipated into the atmosphere (q2) are equal to obtain thermal homeostasis:

$q_1=q_2$
[0058] The absolute core temperature may be determined as:

$T_c=k\times(T_e-T_a)+T_a$
[0059] In the above expression, "k", with (R.sub.1+R.sub.2)/R.sub.1, is an unknown coefficient which may be defined empirically over a range of patients, situations, and also depending on the material property of the earpiece. "T.sub.a" is the ambient temperature ("skin microclimate temperature"). After sensing ear canal temperature and ambient temperature, the absolute core temperature may be calculated. In certain examples, "k" may be written as (1+h/pc), where "h" is the heat transfer coefficient, "p" the blood perfusion rate per unit area at the skin and "c" is the specific heat of blood.
[0060] The hybrid method described above may have the following edge cases:
[0061] If h=0, which means the heat loss is zero, then T.sub.c=T.sub.e. That is, ear canal

temperature is the same as core body temperature.
[0062] If p=∞, which means the perfusion is infinite, then T.sub.c=T.sub.e.
[0063] If T.sub.a=T.sub.c, which means that ambient temperature is near core body temperature, then T.sub.c=T.sub.e.
[0064] The parameter "k" may be estimated to be between −10 and 10. The parameter "k" may be estimated in any suitable manner. For example, the estimation of "k" may be based on a rational selection of possible temperatures of the body, the ambient environment, and/or the ear canal, e.g., skin, of the user.
[0065] In certain examples, system **100** may calibrate either one or both of the temperature sensors (e.g., temperature sensors **216-1** and **216-2**) to facilitate measuring a core body temperature of a user. The temperature sensors may be calibrated in any suitable manner. For example, in certain implementations, both temperature sensors may be calibrated such that no further calibration is necessary. In certain alternative implementations, one of the temperature sensors may be calibrated. The other temperature sensor may then be calibrated during a situation where both of the temperature sensors are away from the user (e.g., while charging in a charging box) and experiencing the same temperature. In certain alternative examples, none of the temperature sensors of the hearing device may be calibrated initially but a calibrated temperature sensor may be provided in an additional device, e.g., an auxiliary device. For example, a charger base may include a calibrated temperature sensor. In such an example, the temperature sensor of the hearing device may become calibrated when they are associated with the additional device (e.g., during charging). In certain implementations, such an additional device may include a UVC light for disinfection purposes, a dry cleaning capability, a pressure sensor to facilitate estimating the temperature, a humidity sensor, a setup for acoustical self-tests of the hearing device, a GPS sensor that may be used to track a location of the additional device if lost, and/or any other suitable component. In some instances, processor **104**, **212** can be configured to determine a situation in which first temperature sensor **216-1** and second temperature sensor **216-2** are exposed to an equal temperature, e.g., ambient temperature T.sub.a, and to calibrate first temperature sensor **216-1** and second temperature sensor **216-2**, e.g., the ear canal temperature data provided by temperature sensor **216-1** and the ambient temperature data provided by temperature sensor **216-2**, relative to the equal temperature. The situation in which first temperature sensor **216-1** and second temperature sensor **216-2** are exposed to the equal temperature may comprise a situation in which the hearing device is removed from the ear of the user. The situation in which first temperature sensor **216-1** and second temperature sensor **216-2** are exposed to the equal temperature may also comprise a situation in which the hearing device is inserted and/or positioned and/or attached and/or coupled to the additional device. In some instances, the additional device may be a charger and processor **104**, **212** may be configured to determine the situation in which first temperature sensor **216-1** and second temperature sensor **216-2** are exposed to an equal temperature based in whether the hearing device is inserted and/or connected to the charger and/or being charged. In some instances, the additional device may be a disinfection device and processor **104**, **212** may be configured to determine the situation in which first temperature sensor **216-1** and second temperature sensor **216-2** are exposed to an equal temperature based in whether the hearing device is exposed to radiation for the disinfection, such as UVC light, and/or the hearing device is inserted and/or connected to the disinfection station.
[0066] FIG. **8** illustrates an exemplary method **800** for measuring a core body temperature of a user according to principles described herein. While FIG. **8** illustrates exemplary operations according to one embodiment, other embodiments may omit, add to, reorder, and/or modify any of the operations shown in FIG. **8**. One or more of the operations shown in FIG. **8** may be performed by core body temperature processing system **100**, a hearing device such as hearing device **202**, a computing device such as computing device **206**, an additional computing device communicatively coupled to computing device **206** and/or hearing device **202**, any components included therein,

and/or any combination or implementation thereof.

[0067] At operation **802**, a core body temperature processing system such as core body temperature processing system **100** may obtain a first temperature reading from a first temperature sensor provided in a hearing device and configured to detect ear canal temperature within an ear canal of a user of the hearing device. Operation **802** may be performed in any of the ways described herein.

[0068] At operation **804**, the core body temperature processing system may obtain a second temperature reading from a second temperature sensor configured to detect ambient temperature outside of the ear canal. Operation **804** may be performed in any of the ways described herein.

[0069] At operation **806**, the core body temperature processing system may obtain a work status of the user indicative of an activity level of the user. Operation **806** may be performed in any of the ways described herein.

[0070] At operation **808**, the core body temperature processing system may determine a core body temperature of the user based on the first temperature reading, the second temperature reading, and the work status of the user. Operation **808** may be performed in any of the ways described herein.

[0071] In some examples, a computer program product embodied in a non-transitory computer-readable storage medium may be provided. In such examples, the non-transitory computer-readable storage medium may store computer-readable instructions in accordance with the principles described herein. The instructions, when executed by a processor of a computing device, may direct the processor and/or computing device to perform one or more operations, including one or more of the operations described herein. Such instructions may be stored and/or transmitted using any of a variety of known computer-readable media.

[0072] A non-transitory computer-readable medium as referred to herein may include any non-transitory storage medium that participates in providing data (e.g., instructions) that may be read and/or executed by a computing device (e.g., by a processor of a computing device). For example, a non-transitory computer-readable medium may include, but is not limited to, any combination of non-volatile storage media and/or volatile storage media. Exemplary non-volatile storage media include, but are not limited to, read-only memory, flash memory, a solid-state drive, a magnetic storage device (e.g., a hard disk, a floppy disk, magnetic tape, etc.), ferroelectric random-access memory (“RAM”), and an optical disc (e.g., a compact disc, a digital video disc, a Blu-ray disc, etc.). Exemplary volatile storage media include, but are not limited to, RAM (e.g., dynamic RAM).

[0073] FIG. **9** illustrates an exemplary computing device **900** that may be specifically configured to perform one or more of the processes described herein. As shown in FIG. **9**, computing device **900** may include a communication interface **902**, a processor **904**, a storage device **906**, and an input/output (“I/O”) module **908** communicatively connected one to another via a communication infrastructure **910**. While an exemplary computing device **900** is shown in FIG. **9**, the components illustrated in FIG. **9** are not intended to be limiting. Additional or alternative components may be used in other embodiments. Components of computing device **900** shown in FIG. **9** will now be described in additional detail.

[0074] Communication interface **902** may be configured to communicate with one or more computing devices. Examples of communication interface **902** include, without limitation, a wired network interface (such as a network interface card), a wireless network interface (such as a wireless network interface card), a modem, an audio/video connection, and any other suitable interface.

[0075] Processor **904** generally represents any type or form of processing unit capable of processing data and/or interpreting, executing, and/or directing execution of one or more of the instructions, processes, and/or operations described herein. Processor **904** may perform operations by executing computer-executable instructions **912** (e.g., an application, software, code, and/or other executable data instance) stored in storage device **906**.

[0076] Storage device **906** may include one or more data storage media, devices, or configurations and may employ any type, form, and combination of data storage media and/or device. For example, storage device **906** may include, but is not limited to, any combination of the non-volatile media and/or volatile media described herein. Electronic data, including data described herein, may be temporarily and/or permanently stored in storage device **906**. For example, data representative of computer-executable instructions **912** configured to direct processor **904** to perform any of the operations described herein may be stored within storage device **906**. In some examples, data may be arranged in one or more databases residing within storage device **906**.

[0077] I/O module **908** may include one or more I/O modules configured to receive user input and provide user output. **1**/O module **908** may include any hardware, firmware, software, or combination thereof supportive of input and output capabilities. For example, I/O module **908** may include hardware and/or software for capturing user input, including, but not limited to, a keyboard or keypad, a touchscreen component (e.g., touchscreen display), a receiver (e.g., an RF or infrared receiver), motion sensors, and/or one or more input buttons.

[0078] I/O module **908** may include one or more devices for presenting output to a user, including, but not limited to, a graphics engine, a display (e.g., a display screen), one or more output drivers (e.g., display drivers), one or more audio speakers, and one or more audio drivers. In certain embodiments, I/O module **908** is configured to provide graphical data to a display for presentation to a user. The graphical data may be representative of one or more graphical user interfaces and/or any other graphical content as may serve a particular implementation.

[0079] In some examples, any of the systems, hearing devices, computing devices, and/or other components described herein may be implemented by computing device **900**. For example, memory **102** and/or memory **210** may be implemented by storage device **906**, and processor **104** and/or processor **212** may be implemented by processor **904**.

[0080] In the preceding description, various exemplary embodiments have been described with reference to the accompanying drawings. It will, however, be evident that various modifications and changes may be made thereto, and additional embodiments may be implemented, without departing from the scope of the invention as set forth in the claims that follow. For example, certain features of one embodiment described herein may be combined with or substituted for features of another embodiment described herein. The description and drawings are accordingly to be regarded in an illustrative rather than a restrictive sense.

Claims

1. A hearing device configured to be at least partially inserted into an ear canal of a user, the hearing device comprising: a first temperature sensor configured to detect an ear canal temperature within the ear canal; a second temperature sensor configured to detect ambient temperature outside of the ear canal; and a processor configured to: determine a work status of the user indicative of an activity level of the user; and determine a core body temperature of the user based on the ear canal temperature detected by the first temperature sensor, the ambient temperature detected by the second temperature sensor, and the work status of the user.

2. The hearing device of claim 1, wherein the processor is further configured to determine the core body temperature of the user based on a heart rate of the user.

3. The hearing device of claim 1, wherein the determining of the core body temperature includes using a linear regression model to estimate the core body temperature.

4. The hearing device of claim 1, wherein the first temperature sensor is a flow temperature sensor, an infrared (IR) thermometer, or a contact temperature sensor.

5. The hearing device of claim 1, wherein: the first temperature sensor is an infrared (IR) thermometer; and the hearing device further includes a housing a having a hollow core optical waveguide configured to enhance coupling efficiency of IR radiation from tissue in the ear canal to the IR thermometer.

6. The hearing device of claim 5, wherein the hollow core optical waveguide has a funnel shape.

7. The hearing device of claim 5, wherein the hollow core optical waveguide has a tube shape.
8. The hearing device of claim 1, wherein: the hearing device further includes a housing having a faceplate that is configured to face outside of the ear canal when the hearing device is worn by the user; and the second temperature sensor is positioned on the faceplate.
9. The hearing device of claim 1, further comprising a behind-the-ear (BTE) component, wherein the second temperature sensor is positioned on the BTE component.
10. The hearing device of claim 1, wherein the hearing device is customized to fit at least partially within the ear canal of the user.
11. The hearing device of claim 1, wherein the processor is further configured to direct the hearing device to provide an audio notification that informs the user of the core body temperature.
12. The hearing device of claim 1, wherein the processor is further configured to: determine a situation in which the first temperature sensor and the second temperature sensor are exposed to an equal temperature; and calibrate the first temperature sensor and the second temperature sensor relative to the equal temperature.
13. The hearing device of claim 1, further comprising a motion sensor, wherein the determining of the work status is based on information received from the motion sensor.
14. A system comprising: a hearing device configured to be at least partially inserted into an ear canal of a user, the hearing device comprising: a first temperature sensor configured to detect ear canal temperature within the ear canal; and a second temperature sensor configured to detect ambient temperature outside of the ear canal; and a processor configured to: determine a work status of the user indicative of an activity level of the user; and determine a core body temperature value of the user based on the ear canal temperature detected by the first temperature sensor, the ambient temperature detected by the second temperature sensor, and the work status of the user.
15. The system of claim 14, further comprising an external device that is communicatively coupled with the hearing device and is configured to present information associated with the core body temperature to the user.
16. The system of claim 15, wherein the processor is included in the external device that is communicatively coupled with the hearing device.
17. The system of claim 14, further comprising an additional hearing device configured to be at least partially inserted into an additional ear canal of a user, the additional hearing device comprising: a third temperature sensor configured to detect ear canal temperature within the additional ear canal; and a fourth temperature sensor configured to detect ambient temperature outside of the additional ear canal, wherein the processor is further configured to determine an additional value of the work status of the user indicative of an activity level of the user, and to determine an additional core body temperature value of the user based on the ear canal temperature detected by the third temperature sensor, the ambient temperature detected by the fourth temperature sensor, and the additional value of the work status.
18. The system of claim 17, wherein the processor is further configured to determine a core body temperature of the user based on the core body temperature value and the additional core body temperature value.
19. A method comprising: obtaining, by a core body temperature processing system, a first temperature reading from a first temperature sensor provided in a hearing device and configured to detect ear canal temperature within an ear canal of a user of the hearing device; obtaining, by the core body temperature processing system, a second temperature reading from a second temperature sensor configured to detect ambient temperature outside of the ear canal; obtaining, by the core body temperature processing system, a work status of the user indicative of an activity level of the user; and determining, by the core body temperature processing system, a core body temperature of the user based on the first temperature reading, the second temperature reading, and the work status of the user.
20. The method of claim 19, further comprising obtaining, by the core body temperature processing

system, a heart rate of the user, wherein the core body temperature of the user is further determined based on the heart rate of the user.