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(54) **AUTOMATED DIAGNOSIS-ASSISTING
MEDICAL DEVICES**

(71) Applicants: **Andreas J. Schrieffl**, Graz (AT);
Andreas J. Reinisch, Graz (AT)

(72) Inventors: **Andreas J. Schrieffl**, Graz (AT);
Andreas J. Reinisch, Graz (AT)

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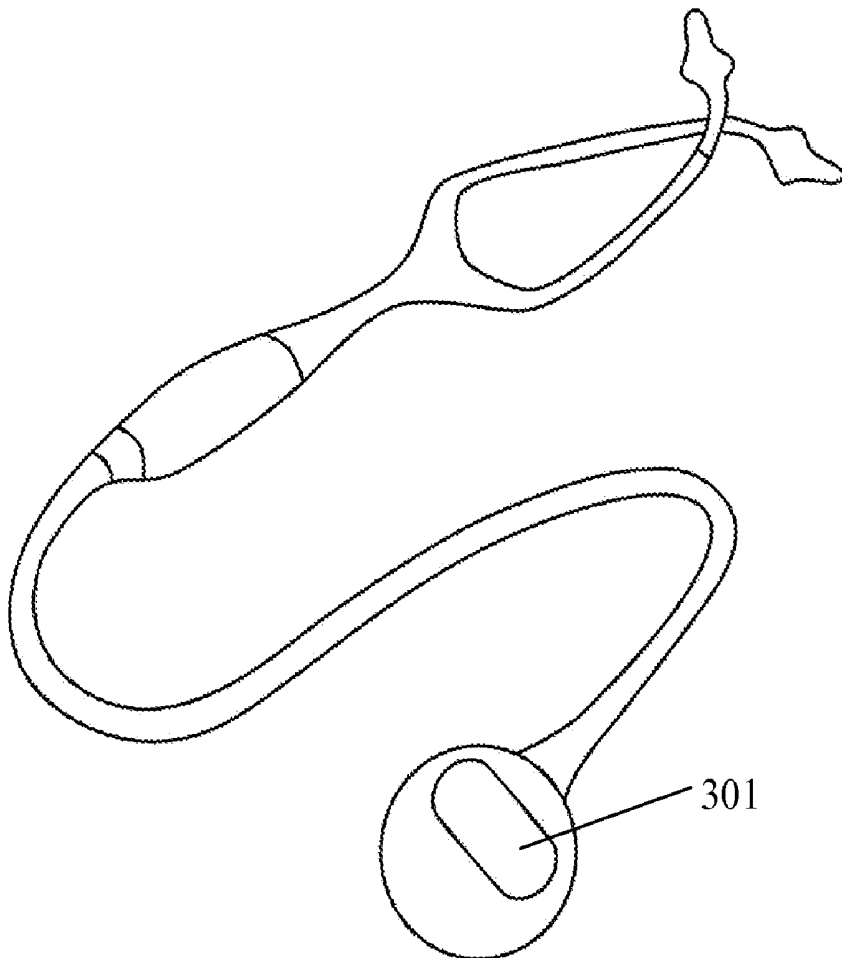
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(57) **ABSTRACT**

A system includes an electronic stethoscope producing a quasi-periodic signal, a processor, and a memory device with stored instructions that, when executed by the processor, cause the system to receive a representation of the quasi-periodic signal, to remove a DC component from the received representation of the quasi-periodic signal to produce a purely time-varying signal, and to filter, the time-varying signal to produce a pre-processed signal. A portion of the pre-processed signal is auto-correlated with itself, and a corresponding auto-correlation output is stored. A biphasic tapering function is applied to the auto-correlation output and produces a first maximum, the function including a time constant parameter that is a function of the quasi-periodic signal. A representation is stored, based on the first maximum, as an indication of a rate or frequency of the quasi-periodic signal.



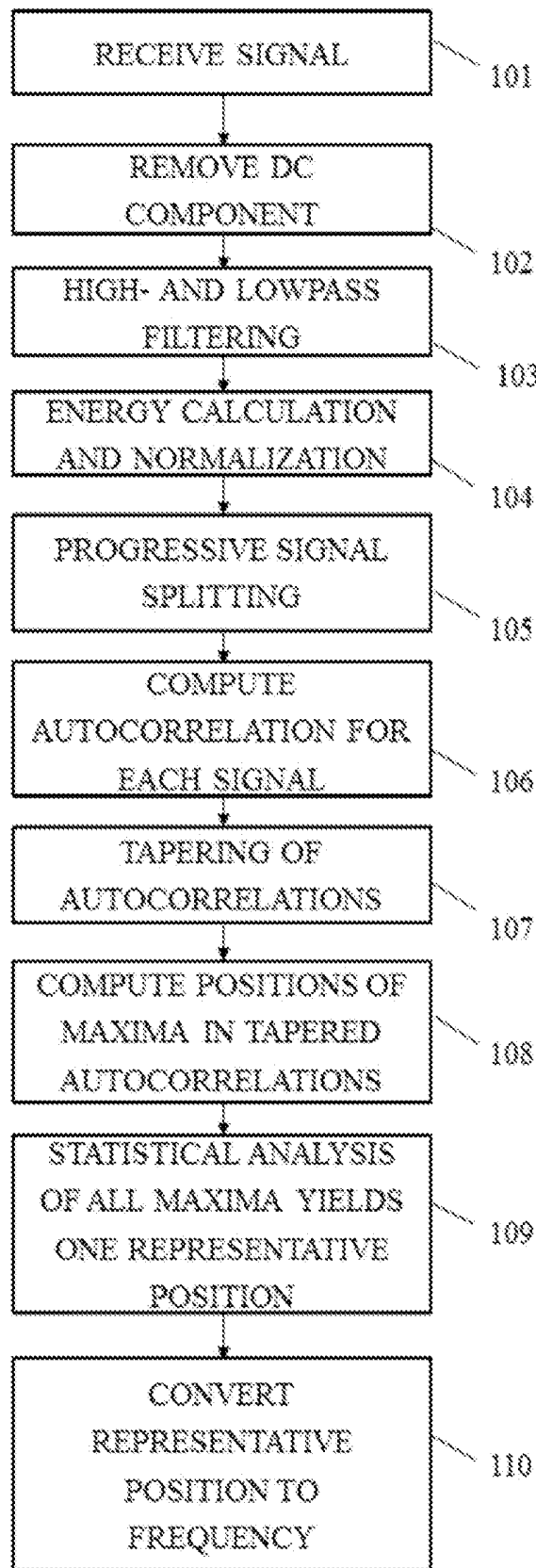


FIG. 1

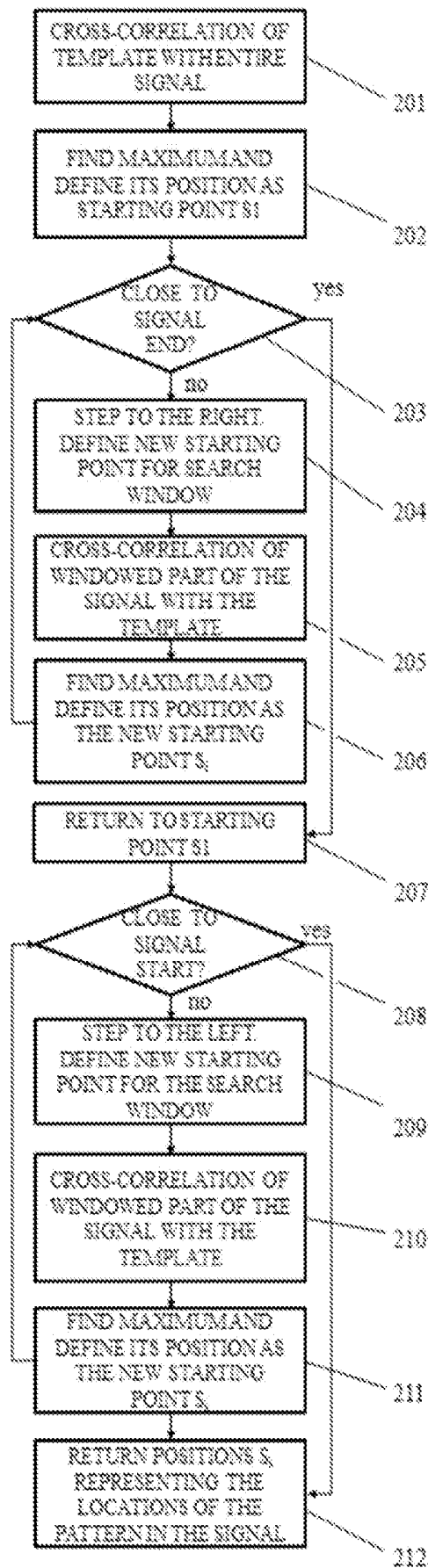


FIG. 2

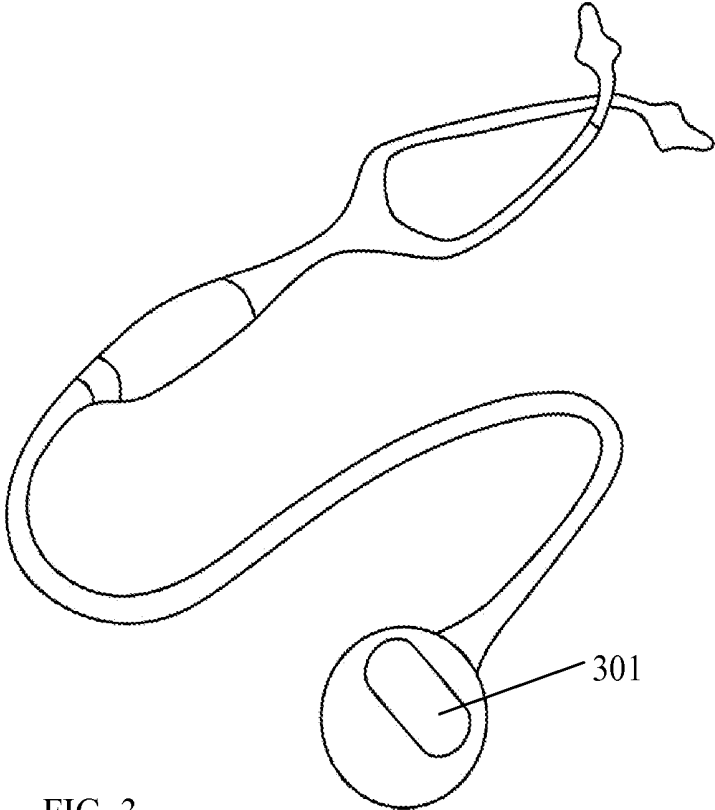


FIG. 3

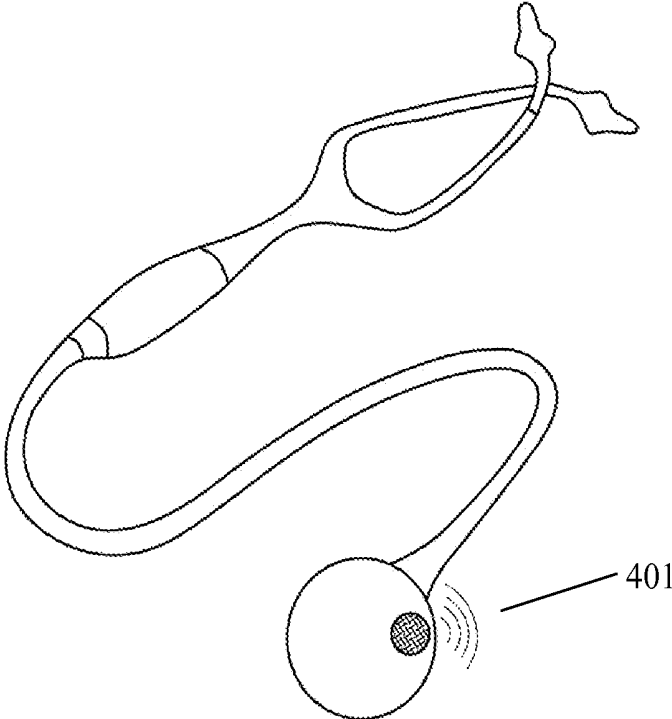


FIG. 4

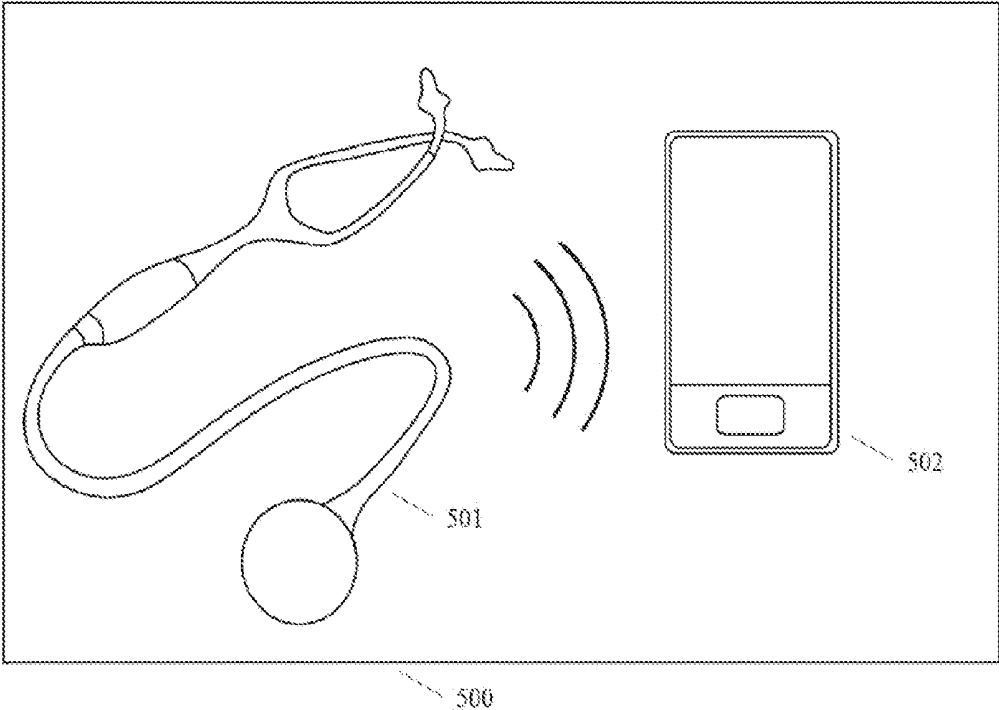


FIG. 5

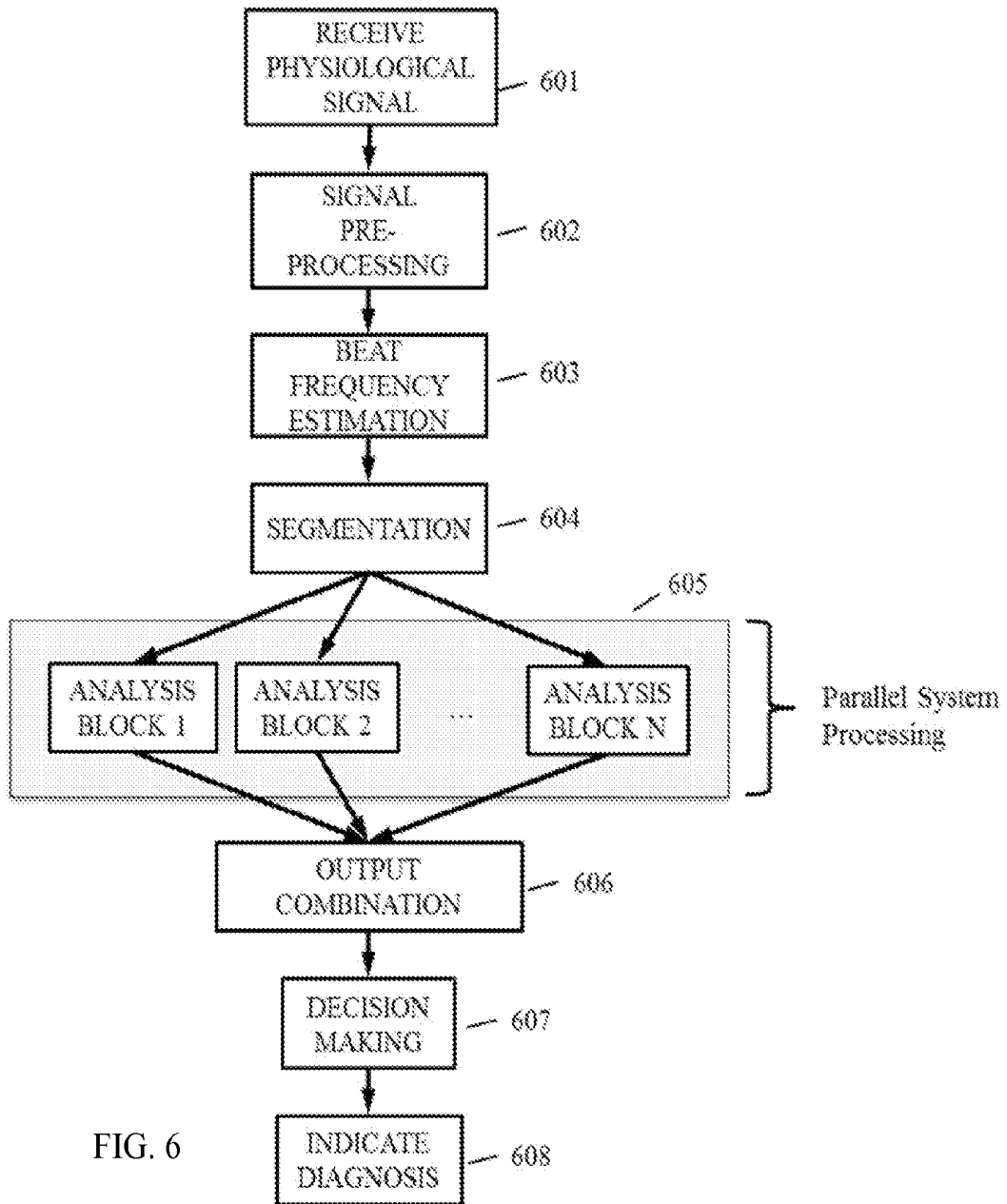


FIG. 6

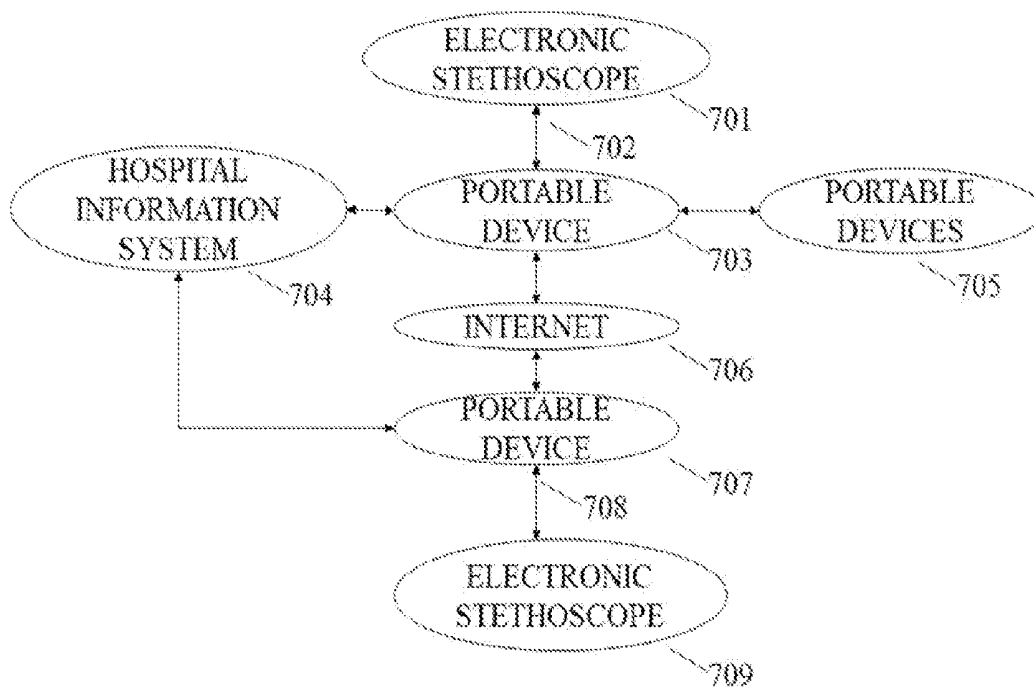


FIG. 7

AUTOMATED DIAGNOSIS-ASSISTING MEDICAL DEVICES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 14/210,026, titled "Automated Diagnosis-Assisting Medical Devices Utilizing Pattern Localization Of Quasi-Periodic Signals," filed Mar. 13, 2014, which claims the benefit of and priority to U.S. Provisional Patent Application No. 61/787,998, titled "Automated Diagnosis-Assisting Medical Devices Utilizing Rate/Frequency Estimation And Pattern Localization Of Quasi-Periodic Signals" and filed on Mar. 15, 2013, each of which is incorporated herein by reference in its respective entirety.

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FIELD OF THE INVENTION

[0003] Various aspects of the present disclosure relate to the estimation of the rate or frequency and to the localization of similar patterns in quasi-periodic signals. More specifically, for example, the signals are not limited to being quasi-periodic and are often overlaid with noise or other artifacts. More generally, some aspects relate to automated signal processing of sounds originating from various body structures for providing clinical referral conditions at a site, such as the patient's site.

BACKGROUND

[0004] Analyzing quasi-periodic signals is very common, e.g., analyzing sounds originating from the heart or lungs, and has long been a tool for evaluating conditions of subjects or patients. Since the existence of the stethoscope, the electrocardiogram device, and similar devices, such practices have been formalized. In the case of the stethoscope, for example, the sound is detected non-invasively at the surface of the skin and evaluated by a skilled practitioner. This is a standard screening method performed worldwide and called auscultation. Interestingly, auscultation is also one of the few remaining routine medical procedures in which the diagnosis is made purely by the medical professional who listens and interprets the sounds originating from the heart or lungs based solely on his or her training and experience.

[0005] With no objective and comparable means of evaluation, the quality of the subjective human diagnosis is solely dependent on the investigating medical professional, inevitably leading to a lack of objectivity and a high variability of findings between medical professionals. As such, making a diagnosis is vulnerable to human error and subjectivity due to a multitude of potential causes (e.g., stressful working environment, lack of sleep, etc.) associated with the medical profession. All of the above identified problems create a huge burden of responsibility for the medical professionals. Additionally, without an independent system in place that supports and documents the medical professionals' findings from the auscultation (including objective, clinically tested, investiga-

tor-independent, patient-specific parameters), the medical professionals lack an objective basis to defend their subjective findings.

[0006] Since the rise of high-speed computing, increasing attention has focused on analyzing digitized quasi-periodic signals through digital signal processing ("DSP") techniques. Often, the DSP techniques have been used simply for determining the rate, frequency, or steadiness of such signals. More recently, the DSP technique have also been used to determine pathological conditions of a medical subject.

[0007] The problem or challenge with such analyses lies in the reliable extraction and classification of significant features, often hidden in the recordings of such variable biological signals. This leads to the importance of proper or correct signal segmentation, which is often performed manually or sometimes automatically on good quality signals. In reality, recorded biological signals in a clinical environment are not of "good" quality, in which case existing systems struggle to yield reliable and robust results. For example, most current approaches of rate detection are simply triggered by the presence of a certain energy level in the signal, which is problematic in environments containing other noise or sounds, such as, for example, people walking or talking, other machines, traffic noise, etc. Other approaches are also detrimental because they require external input, such as, for example, electro cardiogram data, to achieve correct signal segmentation.

[0008] Therefore, there is a need, for example, for handling uncorrelated noise and variations in the periodicity of such variable input signals, and/or for estimating signal rates or frequencies, as well as recognizing and identifying locations of similar patterns. For example, such technology can be utilized as a standalone device or as part of a larger system for automated diagnoses of quasi-periodic signals.

SUMMARY OF THE INVENTION

[0009] According to an aspect of the present disclosure, a method or algorithm is disclosed that estimates a rate or frequency of quasi-periodic signals and localizes similar patterns in quasi-periodic signals without requiring high-end computing powers. Quasi-periodic signals are signals that can potentially be highly irregular while still containing some repeating, often hidden, features. Exemplary signals include biological signals that are concealed by noise and artifacts from various sources, such as originating internally (from a body structure) or externally (from the environment), and that are independent of the signal type or acquisition (e.g., electrical, mechanical, optical, acoustical, etc.). The signals are typically, but not necessarily limited to being quasi-periodic, and are often overlaid with noise or other artifacts.

[0010] Another aspect of the present disclosure is directed to determining a representative estimation of the rate of such signals, e.g., heart beat frequency or breathing frequency. The signal rate from biological sources is often a parameter of interest in clinical settings, but can also be utilized in subsequent or related signal processing stages to perform further analysis. The algorithm includes utilizing a combination of auto-correlation functions, tapering functions, and/or progressive signal splitting and statistical tools to analyze quasi-periodic signals.

[0011] Furthermore, yet another aspect of the present disclosure utilizes signal templates, e.g. a single representative heartbeat in a series of heartbeats or an analytical signal that shows similar features as the pattern of interest in the target

signal, to search throughout the entire signal for locations where similar signal patterns (or shapes) are found. The resulting locations are stored and returned. The algorithm utilizes a sequence of cross-correlation and windowing functions in combination with signal rate estimation that makes the algorithm robust against changes in periodicity, noise, and artefacts.

[0012] According to yet another aspect of the present disclosure, a method or algorithm is disclosed that changes traditional functions of electronic stethoscopes from a device typically capable of recording, storing, and manipulating data, into a device that automatically delivers diagnostic results for clinically relevant referral conditions directly to patient's site. By utilizing, for example, parallel system processing, involving novel algorithms, and physiological parameters that are optimized with findings from clinical studies, an embodiment of the present disclosure relates to a method of analyzing and diagnosing digital physiological signals that were recorded with commercially available electronic stethoscopes.

[0013] According to yet another aspect of the present disclosure, a method of estimating a frequency of a quasi-periodic signal is performed directly by an electronic stethoscope as illustrated in FIG. 3 and FIG. 4. Alternatively, the method is performed by a small, external and portable device connected or linked to the stethoscope, as illustrated in FIG. 5 (e.g., a small device, tablet, smartphone, etc.), but that does not require high-end computing powers. The utilization of one or more aspects of the disclosed algorithm using standard computing resources, e.g., found in state-of-the-art smartphones or tablet computers, is possible due to various attributes of the algorithm, such as further described below.

[0014] According to one attribute, the algorithm uses methods like auto-correlation or cross-correlation, which can be computed very efficiently by using time-frequency conversion to perform such operations. Microprocessors often provide optimized implementations of such time-frequency conversions, such as Fast Fourier Transform ("FFT"), and, therefore, significantly boosting time-domain operations.

[0015] According to another attribute, the algorithm enables fast and efficient computation by using pre-trained classifiers (e.g., neural networks, support vector machines, Bayesian networks, etc.). The pre-trained classifiers facilitate new data to be classified with simple and computationally efficient operations (e.g., matrix multiplications). For this approach, parameters are determined with training data. For example, in reference to neural networks, weights and biases determined with training data. Or, in reference to support vector machines, the location of the support vectors in the hyperspace is determined with training data. Comprehensive and well classified training data is useful for a good pre-training of classifiers. The training data of the disclosed algorithm includes, for example, raw phonocardiogram data and/or corresponding diagnoses (obtained using, for example, echocardiography as the gold standard method for diagnosing heart defects). With a comprehensive training set, a classifier can be optimized (or, pre-trained) and applied to new data, which enables fast and efficient computations. In contrast, so-called lazy-learning methods use the whole available data set (stored locally) and compare new data against the whole training set for classification. The lazy-learning methods lead to higher space requirements for storing the training data set and/or to increased computational costs for performing the classification.

[0016] According to yet another attribute, the features of interest (or inputs to the classifier) are determined in advance by feature selection algorithms (e.g., sequential floating forward selection), which reduce feature space. Features are also analyzed using statistical tools such as a principal component analysis, which results in linearly uncorrelated variables and which further optimizes the feature space. Hence, only the most powerful and meaningful features are selected for the algorithm, increasing its computational efficiency and robustness against noise and outliers.

[0017] According to yet another aspect of the present disclosure, a method and/or system includes combining an electronic stethoscope with a portable device (FIG. 5) for automated analysis and diagnosis-support for stethoscope-based auscultation. The method and/or system utilizes one or more of the algorithms described below in reference to FIGS. 1, 2, and/or 6. The analysis is performed by the portable device, which provides results including a set of patient-specific parameters and/or indicators. The results are investigator independent and include medical and technical parameters, such as heart and/or breathing rate, heart and/or breathing rate variability, systolic and diastolic energy, signal curve, diagnosis suggestion, etc. At least some of these objective parameters and/or other results are displayed and/or stored on the portable device as a means for diagnosis support for the medical professional or other user.

[0018] According to yet another aspect of the present disclosure, a bidirectional system architecture is illustrated in FIG. 7 for enabling a device to be utilized for one or more of the following purposes:

[0019] (i) documentation purposes including, for example, saving all data and results in a common file format (e.g., PDF format), printing, emailing, bidirectional integration into a hospital information system ("HIS"), and/or efficient filing of all data and results to a patient's medical file;

[0020] (ii) teaching, training, research, and/or presentation purposes by wirelessly connecting the portable device to a single or multiple other portable devices that receive all data, including the results obtained with the utilization of one or more of the described algorithms; and/or

[0021] (iii) bidirectional tele-auscultation for remote auscultation allowing the user to remotely control settings of an electronic stethoscope at a patient's site (e.g., change filters, adjust volumes, etc.), to communicate with a person operating the electronic stethoscope (e.g., instructing the person to change the position of the stethoscope), and to further provide documentation and HIS integration.

[0022] According to yet another aspect of the present disclosure, a bidirectional system architecture is disclosed as illustrated in FIG. 7 and in which the HIS is utilized to host or run one or more of the described algorithms. The system allows a user to access the system via a portable device or any computer connected to the HIS. Optionally, recorded signal data is uploaded and/or stored in the HIS. The data is analyzed by the HIS directly and/or the data is downloaded onto the portable device for later or remote analysis.

[0023] According to other aspects of the present disclosure, the device does not require any external input from medical professionals or other devices (e.g., ECG), does not require traditional auscultation techniques to be modified, does not require especially quiet environments (such as, for example,

the holding of breath by the patient during auscultation), and/or does not require manual or semi-automated analysis by a medical professional. Alternatively, adding an external input by the user is optional and does not hinder the device from performing its tasks. In fact, the external input might potentially even increase the accuracy of the results.

[0024] By way of example, in reference to a phonocardiogram analysis, the age of the patient is a helpful parameter for narrowing down the range of likely heart rates and possible diseases (e.g., a specific classification of a heart murmur). A newborn, for example, usually has a heart rate greater than 100 beats per minute and the range of possible diseases is generally different than, for example, for a child greater than 2 years of age. One or more features of the present disclosure are beneficial to and enhance existing electronic stethoscopes by increasing their function as a medical device and informing medical staff within a short period of time whether physiological signals are healthy or require further medical attention. Thus, one or more features of the present disclosure can be utilized directly on an electronic stethoscope or in combination with an electronic stethoscope and a portable device, wherein computations and interaction (e.g., visualization of the findings) with medical staff are achieved through the portable device.

[0025] According to one embodiment of the present disclosure, a system for processing a quasi-periodic signal includes an electronic stethoscope that produces a quasi-periodic signal, a processor, and a memory device with stored instructions that, when executed by the processor, cause the system to receive a representation of the quasi-periodic signal. A DC component is removed from the received representation of the quasi-periodic signal to produce a purely time-varying signal, and the time-varying signal is filtered to produce a pre-processed signal. At least a portion of a representation of the pre-processed signal is auto-correlated with itself, and a corresponding auto-correlation output is stored for the at least portion of the representation of the pre-processed signal. A biphasic tapering function is applied to the auto-correlation output, the tapering function including a time constant parameter that is a function of the quasi-periodic signal and producing a first maximum. A representation is stored, based on the first maximum, in the memory device as an indication of a rate or a frequency of the quasi-periodic signal.

[0026] According to another embodiment of the present disclosure, a system for processing a quasi-periodic signal includes an electronic stethoscope that produces a quasi-periodic signal, a processor, and a memory device with stored instructions that, when executed by the processor, cause the system to, in response to receiving a representation of the quasi-periodic signal, produce a pre-processed time-varying signal. An auto-correlation output is produced that corresponds to an auto-correlation of at least a portion of a representation of the pre-processed time-varying signal with itself. In response to applying a biphasic tapering function to the auto-correlation output, a frequency of the quasi-periodic signal is estimated, and a search window is defined based on the estimated frequency of the quasi-periodic signal. A starting position is defined in the received quasi-periodic signal, the starting position corresponding to a first maximum. A portion of the quasi-periodic signal is cross-correlated in the search window with a template signal pattern to be matched to produce a second maximum that is defined by the controller as a new starting position, which is stored.

[0027] The foregoing and additional aspects and embodiments of the present disclosure will be apparent to those of ordinary skill in the art in view of the detailed description of various embodiments and/or aspects, which is made with reference to the drawings, a brief description of which is provided next.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] These and other features of exemplary implementations of the present disclosure will become apparent from the description, and the accompanying drawings. According to common practice, various features of the drawings are not to scale but are purposefully modified arbitrarily for improved clarity wherein:

[0029] FIG. 1 is a diagrammatic illustrating a process of rate or frequency estimation in quasi-periodic signals.

[0030] FIG. 2 is a flowchart illustrating a process for localization of similar patterns in quasi-periodic signals.

[0031] FIG. 3 is a representative illustration of an electronic stethoscope that includes a display for visual indication of a resulting diagnosis.

[0032] FIG. 4 is a representative illustration of an electronic stethoscope that acoustically indicates a resulting diagnosis.

[0033] FIG. 5 is a representative illustration of an electronic stethoscope that is connected to an external, portable device (e.g., a small device, tablet, smartphone, etc.) for indication (visually, acoustically, or otherwise) of resulting findings including diagnosis suggestion.

[0034] FIG. 6 is a flowchart illustrating an exemplary method of digital signal processing of physiological signals.

[0035] FIG. 7 outlines a bidirectional system architecture for achieving documentation, teaching, and/or bidirectional tele-auscultation.

DETAILED DESCRIPTION OF THE INVENTION

[0036] Referring to FIG. 1, a diagrammatic illustrates a rate/frequency estimation algorithm in accordance with one aspect of the present disclosure. At **101**, a quasi-periodic input signal, such as an acoustical signal indicative of a physiological rhythm (e.g., heartbeat, respiration), is loaded. At **102**, a DC component is removed from the input signal, s , according to $s_{DCrem} = s - \text{mean}(s)$, where

$$\text{mean}(x) = \frac{1}{N} \sum_{n=1}^N x(n)$$

is the mean operator, s_{DCrem} is the input signal having its DC component removed, and N is the length of x .

[0037] At **103**, filtering of the input signal is applied to produce a pre-processed signal that emphasizes the quasi-periodic patterns of the signal for rate estimation (e.g., the heart sound S1 and S2 in a phonocardiogram). The filtering is performed with a standard band-pass filter (high-pass filtering and/or low-pass filtering) or with wavelet filtering. In accordance with wavelet filtering, the signal is decomposed into detail and approximation coefficients, and, as such, thresholding of the detail coefficients with subsequent reconstruction of the signal enables noise removal. Corresponding cut-off frequencies, filter types, and threshold levels in **103** are dependent on the type of input signal. Examples of input signals include heart sounds, breathing sounds, bowel

sounds, quasi-periodic signals, etc. Furthermore, threshold levels are not directly dependent on the type of input signal, but are computed specifically for each input signal.

[0038] At **104**, from the now pre-processed signal, signal energy is calculated and normalized, e.g.,

$$s_{norm} = s_{filt} / \sqrt{\frac{1}{N} \sum_{n=1}^N s_{filt}(n)^2},$$

where the denominator corresponds to the root mean square of the signal, where s_{filt} is the filtered, pre-processed signal, and N denotes the length of s_{filt} . If permitted by signal length, at **105** the signal energy is split into progressively smaller time domains, by continuously dividing the entire pre-processed signal energy in halves, thirds, quarters, etc. The splitting of the signal energy continues as long as the length of the smallest resulting domain contains sufficient information for a meaningful analysis.

[0039] For example, if a medical professional is interested in analyzing heartbeats, the size of the smallest domains would have to be large enough to cover the main features of a few heartbeats. Every resulting signal energy domain is stored accordingly in a memory device of a computer or computing device.

[0040] At **106**, for each domain of the energy the auto-correlation of the domain itself is computed and stored, yielding auto-correlations for every domain. A normalized version of the auto- and cross-correlation is used, which compensates for the differences in signal magnitudes and properly correlates a shorter signal with a longer one. This normalized version divides the results of the correlation by the energy of the parts of the signals that were effectively correlated.

[0041] First, the shorter signal s_2 is zero-padded to have equal length as the longer signal s_1 . Second, the standard cross-correlation of s_1 and s_2 is performed by $temp = s_1 \star s_2$, where $temp$ includes only the positive terms, i.e., the second half, of the standard cross-correlation (\star is the cross-correlation operator). Third, the masked energy correlation, en_m , is computed according to $en_m = s_1^2 \star ones(\text{length}(s_2))$, where the latter term represents a rectangular window with the length equal to the length of the shorter signal s_2 . Fourth, the result of the normalized cross-correlation, res_{cc} , is computed according to

$$res_{cc} = \frac{temp}{\text{abs}(\sqrt{en_m}) + \text{abs}(\sqrt{s_2, s_2})},$$

where the dot product $s_2 \cdot s_2$ is used. Since a convolution in the time domain corresponds to a multiplication in the frequency domain, efficient computation is achieved, e.g., computing auto-correlation of $s(t)$, $res_{cc} = \text{IFFT}(F_s(f) * F_s^*(f))$, where $F_s(f) = \text{FFT}(s(t))$ is the FFT of $s(t)$, $F_s^*(f)$ denotes the complex conjugate, and IFFT performs the Inverse Fast Fourier Transform.

[0042] At **107**, a tapering function is applied to every auto-correlation to amplify the relevant maximum in the auto-correlation. To amplify the first maximum representing the rate or frequency, the tapering function is biphasic, where the two phases are selected depending on the input signal but can generally include a rising edge followed by a trailing edge. The biphasic function is necessary because the auto-correla-

tion function of quasi-periodic signals features multiple peaks, and the biphasic nature of the tapering function allows the selection of the most probable (single) peak (by tapering other, more improbable peaks) representing the period of interest. The tapering function additionally includes a time constant as a parameter that also depends on the input signal and that is pre-determined from, for example, values reported in the literature (e.g., average breathing/heart rates for different patient groups) or suitable clinical data if available.

[0043] An example of a biphasic tapering function, $f_{taper}(t)$, is the following exponential function

$$f_{taper}(t) = \frac{t}{T_c} e^{-t/T_c},$$

where T_c is a time constant and t is the time. The two phases of the tapering function are reflected in the first term, which represents a linear increase (e.g., a rising edge or phase), and the second term representing an exponential decline (e.g., a trailing edge or phase). Although other biphasic tapering functions could be used to amplify the maximum in the auto-correlation representing the period time, the exemplary exponential form described above is suitable for estimating a frequency specific in phonocardiograms, based on determinations of clinical phonocardiogram data covered in substantial amount of noise.

[0044] The exemplary biphasic tapering function yielded the best results for selecting the single peak in the auto-correlation function that correlates best with the heart rate of the patient. The maximum of this particular tapering function is $t = T_c$ (as can be seen by setting the first derivative of f_{taper} to zero,

$$f'_{taper} = \frac{T_c - t}{T_c^2} e^{-t/T_c} = 0).$$

Furthermore, T_c is computed by $T_c = 1/f$, where f is the most probable frequency in the signal, which is determined from reported values in the literature or clinical data. By way of example, for very young children (during the first few months of life) a time constant in the range of 0.6 to 0.3 is appropriate and corresponds to an average heart rate between about 100-200 beats per minute.

[0045] At **108**, the positions of the maxima in the tapered auto-correlations are computed and stored in a memory device. At **109**, standard statistical measures such as, for example, mean, median, standard deviation, variance, or other tools (e.g., maximum likelihood estimation) are utilized to determine one representative position for all maxima. Finally, at **110** the one representative position of all maxima of the tapered auto-correlations is converted, yielding the representative signal rate or signal frequency.

[0046] Referring to FIG. 2, a flowchart is directed to outlining a process for the localization of similar patterns in quasi-periodic signals. This process does not require any external input, such as an ECG signal for segmentation or other purposes. The localization algorithm calls for a template representing a signal pattern to be matched to similar patterns throughout the signal. For example, in a physiological signal of a series of heartbeats, the template can be one of the heartbeats in the series.

[0047] The template can also be an analytical signal that shows similar features as the pattern of interest in the target signal. For example, for a phonocardiogram, a primitive template includes two waveforms representing S1 and S2 that are shifted in time, depending on the estimated heart rate. Examples of such waveforms that feature certain similarities with S1 and S2 include the Shannon wavelet

$$\Psi_{shannon}(t) = \text{sinc}\left(\frac{t}{2}\right) \cos\left(\frac{3\pi t}{2}\right)$$

and the real part of the Morlet wavelet

$$\Psi_{morlet}(t) = c_G \pi^{-\frac{1}{4}} e^{-\frac{t^2}{2}} (e^{i\kappa_G t} - \kappa_G),$$

where c_G and κ_G are constants.

[0048] At **201**, the template is cross-correlated with the entire input signal, such as a physiological signal. The maximum of the cross-correlation represents the best match of the template with the signal, and at **202** the position of the maximum is defined as the starting position S1 for the localization algorithm.

[0049] At **203**, the localization algorithm checks if the remaining signal length after the S1 position is long enough to contain the search window specified at **204**. If yes, the algorithm steps to the right of S1 (forward in time) where a new starting point is defined for a search window, shown at **204**. The step size, as well as the size of the search window in **204**, is based on an estimated signal frequency or signal rate, which, for example, is estimated with the algorithm described in FIG. 1 above.

[0050] At **205**, the windowed part of the signal is cross-correlated with the template. At **206**, the position of the maximum in the cross-correlation is computed and stored in a memory device as the new starting point S_i . The maximum represents the best match of the template with the signal within the search window. Next, the localization algorithm goes back to **203** to check if it has arrived close to the signal end. If not, modules **204-206** are repeated. If yes, the algorithm goes back to the starting position S1, according to **207**.

[0051] Throughout modules **208-211**, the localization algorithm performs the same operations as in modules **203-206**, but instead of stepping to the right the algorithm keeps stepping to the left of S1 (back in time). The step size as well as the size of the search window throughout modules **208-211** are again based on an estimated signal frequency or signal rate, but are not necessarily the same as at modules **203-206**. Examples of such step sizes suitable for auscultation data from new-borns are $0.6 * T_p$ for the start and $1.8 * T_p$ for the end of the search window to the right, and $1.4 * T_p$ and $0.2 * T_p$ for the length of the search window, where

$$T_p = \frac{1}{f}$$

is the period.

[0052] When the localization algorithm arrives at a position too close to the signal start (the left end of the signal), where the remaining part of the signal to the left is too short to

contain a new search window, **208** ensures that the localization algorithm jumps to **212**, where all stored positions S_i are returned. The positions S_i represent the locations of the patterns throughout the signal that match the template. This process can be repeated for different patterns of the same input signal. The input signal is not limited to being quasi-periodic and can include a significant amount of noise or artefacts. Furthermore, this process is independent of the type of signal or signal acquisition (e.g., electrical, mechanical, optical, acoustical, etc.).

[0053] Advantages of using a search window include that the signal does not have to be strictly periodic and repeating patterns can still be found. Moreover, the window restricts the search area to a reasonable size, ensuring that patterns covered in noise can also be detected using a template containing similar features as the desired pattern. Ultimately, the lengths and positions of the search windows depend on the signal, keeping in mind that longer windows allow the signal to be more irregular while making the pattern detection in noisy signals more complicated. The position and length of the window is selected such that it does not contain two or more of the patterns of interest, otherwise one of the multiple patterns might be skipped.

[0054] Referring to FIG. 6, a flow chart illustrates modifying an electronic stethoscope into a diagnosis-assisting tool providing additional medically relevant information regarding the physiological signal. At **601**, a quasi-periodical, digital physiological signal is received from an electronic stethoscope. Then, the signal is pre-processed (e.g. filtered, normalized, etc.) at **602**.

[0055] The beat frequency is estimated at **603** using, e.g., the algorithm illustrated in FIG. 1 and used in the segmentation stage at **604**, which is also illustrated in FIG. 2. This segmentation at **604** yields the segments of interest of the signal, e.g., the systole and/or diastole of each heart beat, and/or the inhale and/or exhale phase of a breath.

[0056] In a parallel system processing stage, for example, at **605**, various analysis modules operating in both the frequency and the time domain are applied to extract features of the segments obtained at **604**. For example, such features include an Energy Analysis, Timing Features (e.g., Heart Rate Variability, Duration of S1/Systole/S2/Diastole, etc.), Fourier Transform, Short Time Fourier Transform, Higher Order Statistics (e.g., Bispectra, Gaussian Mixture Models, etc.), Discrete and Continuous Wavelet Analysis, Fractal Dimension Analysis, Stockwell-Transform, Error Entropy Analysis, etc. The output of the parallel modules at **605** is combined at **606** and passed to **607**, where the output is used in a decision making stage. If external data, such as patient age or certain aspects of patient's medical history, is added, classification of specific pathologies might yield increasing accuracy.

[0057] The output of **607** is forwarded to **608** where the diagnosis is indicated to the user on an electronic display device. The diagnosis is indicated, for example, via a binary output, via probabilities, via an acoustic signal, and/or via a visual interface. The visual interface can include a detailed listing of the findings, including a diagnosis suggestion, all of which are optionally stored in a memory device on an electronic stethoscope or shared, stored or printed through other means as described above.

[0058] Additionally, still referring to FIG. 6, a basic structure of a digital signal processing is utilized by one or more aspects of the invention. Parallelization, in combination with

one or more of the above described algorithms and in combination with specific parameters obtained through clinical studies enable a fully automated analysis without requiring any external input in addition to the physiological signal itself (although external data and/or parameters can be optionally added). The diagnostic result is revealed directly on the electronic stethoscope (e.g., FIGS. 3-5) or the portable device that is connected to the electronic stethoscope (e.g., on display 502 of FIG. 5), either visually (through a display 301, 502) or acoustically (e.g., sound emitter 401).

[0059] Some or all modules described above, which have been described by way of example herein, represent one or more algorithms that correspond to at least some instructions executed by one or more controllers to perform the functions or modules disclosed. Any of the methods or algorithms or functions described herein can include machine or computer-readable instructions for execution by a processor, controller, computer, and/or any other suitable processing or computing device. Any algorithm, software, and/or method disclosed herein can be embodied as a computer program product having one or more non-transitory tangible medium or media, such as, for example, a flash memory, a CD-ROM, a floppy disk, a hard drive, a digital versatile disk ("DVD"), or other memory devices. However, persons of ordinary skill in the art will readily appreciate that the entire algorithm and/or parts thereof can alternatively be executed by a device other than a controller and/or embodied in firmware or dedicated hardware (e.g., it can be implemented by an application specific integrated circuit ("ASIC"), a programmable logic device ("PLD"), a field programmable logic device ("FPLD"), discrete logic, etc.).

[0060] Referring to FIG. 5, illustrates a method or system for automated analysis and diagnosis-support for stethoscope-based auscultation. An automated analysis and diagnosis-support system 500 includes an electronic stethoscope 501 with signal transmitting capabilities, which include, for example, an integrated Bluetooth transmitter and/or an appropriate transmitter for transmitting signals directly connected (e.g., via an audio jack) to the electronic stethoscope 501. The transmitter is capable of converting an analog signal to a digital signal and is optionally capable of encrypting the signal.

[0061] For example, heart sounds are transmitted to a processing unit 502, which can be included in a smartphone, a tablet, a computer, etc. The processing unit 502 automatically analyzes the transmitted signal with the utilization of one or more of the algorithms described above. The analysis yields a set of patient-specific parameters/indicators and results, including medical and technical parameters such as heart/breathing rate, heart/breathing rate variability, systolic and diastolic energy, signal curve, diagnosis suggestion (e.g., through probabilities or binary output), etc. All or a selection of these objective parameters and results are displayed and/or stored on the portable device as a means for diagnosis support for the medical professional.

[0062] Referring to FIG. 7, a bidirectional system architecture is illustrated for use with one or more of the algorithms described above for analyzing a signal, enabling a portable device 703 to be utilized for (i) documentation, (ii) teaching, and/or (iii) bidirectional tele-auscultation purposes.

[0063] In reference to documentation, items 701-704 illustrate utilizing an automated, analysis and diagnosis-support system 500 for documentation purposes. All data and results are saved as a common file type (e.g., PDF format) on the

portable device 703, printed, and/or emailed. A bidirectional interface between the portable device 703 and the HIS 704 allows for retrieving of patient data from the HIS if required by the medical professional. The bidirectional interface further allows efficient filing of all data and results to the patient's medical file.

[0064] In reference to teaching, items 701-703 and 705 illustrate utilizing the automated, analysis and diagnosis-support system 500 for stethoscope-based auscultation as described above. The teaching, which is optionally directed to achieving training, research, and/or presentation objectives, is achieved by wirelessly connecting the portable device 703 to a single or multiple other portable devices 705. The portable devices 705 receive all data including the findings of the analysis system. According to one example, a professor teaches medical students the art of auscultation by performing auscultation using the electronic stethoscope 701 on one student and transmitting all related data and results of the system on the portable device 703 to the portable devices 705 of other students.

[0065] In reference to bidirectional tele-auscultation, items 701-703 and 706-709 illustrate a possibility for utilizing the automated, analysis and diagnosis-support system for stethoscope-based auscultation remotely through bidirectional tele-auscultation. In such a scenario, the data is transmitted from the first electronic stethoscope 701 (e.g., operated by a nurse or by the patient himself), through a data link 702 to the portable device 703. The data is further transmitted through a data connection 706 (e.g., the Internet) to a second portable device 707 (operated, e.g., by the medical professional performing the auscultation), and optionally through another data link 708 to a second electronic stethoscope 709 (operated, e.g., by the medical professional performing the auscultation).

[0066] In the above scenario, the first portable device 703 performs the required transmitting functions (with no analysis of the signal), and the second portable device 709 has the automated, analysis and diagnosis-support system for stethoscope-based auscultation running. The bidirectionality of this pathway (701-703 and 706-709) allows the medical professional operating the second portable device 707 to control the settings of the electronic stethoscope 701 (e.g., change filters, adjust volumes, etc.) and to communicate with the person operating the electronic stethoscope through the first stethoscope 701 or the portable device 703 (e.g., instructing the person to change the position of the stethoscope). Documentation and HIS integration are options in the scenario.

[0067] Optionally, the automated analysis and diagnosis-support system illustrated in FIG. 5 is installed and/or hosted by the HIS (e.g., HIS 704 of FIG. 7) and the user accesses the HIS via a portable device (e.g., portable devices 703, 707 of FIG. 7) or via a computer connected to the HIS. In such a case, the recorded signal data is optionally uploaded and/or stored in the HIS and is analyzed in the HIS directly utilizing one or more of the algorithms described above, and/or the data is downloaded onto the portable device for later or remote analysis utilizing one or more of the algorithms described above.

[0068] By way of a specific example, a medical professional uses an electronic stethoscope while medically evaluating a 10 year-old patient. The electronic stethoscope includes a communication input for connecting with a portable device. The medical professional connects the portable device (e.g., a smartphone) (a) to the hospital information

system to receive the patient's medical data (e.g., age, medical history, etc.) and (b) to the electronic stethoscope. The communication input of the electronic stethoscope includes, for example, a built-in Bluetooth chip or an external Bluetooth transmitter connected an audio jack.

[0069] During the medical evaluation in which auscultation is performed, the electronic stethoscope records an acoustic heart signal while the medical professional listens to the heart sound. The electronic stethoscope converts the acoustic heart signal from an analog format into a digital format and transfers the digitized signal to the smartphone. The smartphone receives the digitized signal and processes it, including removing the DC component, filtering, etc.

[0070] After the processing of the digitized signal, the smartphone estimates the heart rate by partitioning the signal, auto-correlating the individual parts, applying a tapering function to each autocorrelation, and statistically analyzing the maxima of all autocorrelations. Then, the heart rate serves as the input for the segmentation stage, where a representative template (e.g., a template pre-stored on the smartphone) is correlated with the digitized signal to find the best matches of this template in the digitized signal within defined search windows.

[0071] The segmentation results from the previous modules are used in a feature extraction stage, where characteristic properties (or features) from the digitized signal are extracted (e.g., via Fourier Transform, Gaussian Mixture Models, Energy Analysis, etc.). These features serve as the input for a decision stage, in which the features are classified, for example, via Multilayer Perceptrons, Support Vector Machines, and/or a combination/cascade of such classifiers. The classifiers yield a diagnosis suggestion and/or a set of patient-specific parameters that are displayed for the medical professional via the smart phone. Results are optionally stored on the smart phone, and/or printed, sent via e-mail, and/or stored in the hospital information system.

[0072] Each of these embodiments and obvious variations thereof is contemplated as falling within the spirit and scope of the claimed invention, which is set forth in the following claims. Moreover, the present concepts expressly include any and all combinations and subcombinations of the preceding elements and aspects.

What is claimed is:

1. A system for processing a quasi-periodic signal, the system comprising:

- an electronic stethoscope producing a quasi-periodic signal;
- a processor; and
- a memory device with stored instructions that, when executed by the processor, cause the system to:
 - receive a representation of the quasi-periodic signal,
 - remove a DC component from the received representation of the quasi-periodic signal to produce a purely time-varying signal,
 - filter, the time-varying signal to produce a pre-processed signal,
 - auto-correlate, at least a portion of a representation of the pre-processed signal with itself,
 - store a corresponding auto-correlation output for the at least portion of the representation of the pre-processed signal,
 - apply a biphasic tapering function to the auto-correlation output, the tapering function including a time

constant parameter that is a function of the quasi-periodic signal and producing a first maximum, and store in the memory device a representation, based on the first maximum, as an indication of a rate or a frequency of the quasi-periodic signal.

2. The system of claim 1, wherein the representation of the quasi-periodic signal includes a heartbeat and a respiration.

3. The system of claim 1, wherein the memory device further causes the system to provide selectable settings of the electronic stethoscope and to communicate between a user of the electronic stethoscope and a medical professional.

4. The system of claim 1, wherein the memory device further causes the system to provide an indication of the rate or the frequency of the quasi-periodic signal directly on a device selected from a group consisting of the electronic stethoscope, a second device attached to the electronic stethoscope, and a third device in wireless communication with the electronic stethoscope.

5. The system of claim 1, wherein the memory device further causes the system to:

estimate the rate or the frequency of the quasi-periodic signal;

define a search window based on the estimated rate or frequency of the quasi-periodic signal;

define a starting position in the received quasi-periodic signal, the starting position corresponding to the first maximum;

cross-correlate a portion of the quasi-periodic signal in the search window with a template signal pattern to be matched to produce a second maximum that is defined by the controller as a new starting position; and

store the new starting position.

6. The system of claim 5, wherein the memory device further causes the system to:

determine a localized pattern of the template signal pattern;

extract a signal segment from the localized pattern;

analyze the signal segment simultaneously in time and frequency domains to produce parallel outputs;

combine the parallel outputs via a statistical or mathematical function to produce a result; and

automatically indicate a diagnosis based on the result.

7. The system of claim 6, wherein the memory device further causes the system to indicate the diagnosis directly on a device selected from a group consisting of the electronic stethoscope, a second device attached to the electronic stethoscope, and a third device in wireless communication with the electronic stethoscope.

8. The system of claim 6, wherein the memory device further causes the system to indicate the diagnosis via one or more of a display and audio output of a portable device.

9. The system of claim 1, wherein the memory device further causes the system to:

share with one or more portable devices data associated with the representation; and

display the data on displays of the one or more portable devices.

10. A system for processing a quasi-periodic signal, the system comprising:

an electronic stethoscope producing a quasi-periodic signal;

a processor; and

a memory device with stored instructions that, when executed by the processor, cause the system to:

in response to receiving a representation of the quasi-periodic signal, produce a pre-processed time-varying signal,
 produce an auto-correlation output corresponding to an auto-correlation of at least a portion of a representation of the pre-processed time-varying signal with itself,
 in response to applying a biphasic tapering function to the auto-correlation output, estimate a frequency of the quasi-periodic signal,
 define a search window based on the estimated frequency of the quasi-periodic signal;
 define a starting position in the received quasi-periodic signal, the starting position corresponding to a first maximum;
 cross-correlate a portion of the quasi-periodic signal in the search window with a template signal pattern to be matched to produce a second maximum that is defined by the controller as a new starting position; and
 store the new starting position.

11. The system of claim **10**, wherein the electronic stethoscope includes selectable settings for communicating between a user of the electronic stethoscope and a medical professional.

12. The system of claim **10**, wherein the electronic stethoscope includes an indication of the frequency of the quasi-periodic signal.

13. The system of claim **10**, wherein the memory device further causes the system to provide an indication of the rate or the frequency of the quasi-periodic signal directly on a device selected from a group consisting of the electronic stethoscope, a second device attached to the electronic stethoscope, and a third device in wireless communication with the electronic stethoscope.

14. The system of claim **10**, wherein the memory device further causes the system to:

determine a localized pattern of the template signal pattern;
 extract a signal segment from the localized pattern;
 analyze the signal segment simultaneously in time and frequency domains to produce parallel outputs;
 combine the parallel outputs via a statistical or mathematical function to produce a result; and
 automatically indicate a diagnosis based on the result.

15. The system of claim **14**, wherein the electronic stethoscope further includes at least one of a display and an audio output feature, the memory device further causing the system to indicate the diagnosis via one or more of the display and the audio output feature.

16. The system of claim **10**, wherein the electronic stethoscope includes a data connection, the memory device further causing the system to:

share, via the data connection, the representation of the frequency with a hospital information system;
 retrieve a patient list from the hospital information system;
 select a patient from the patient list;
 obtain patient specific parameters associated with the representation of the frequency; and
 transfer to the hospital information system one or more of patient data, raw auscultation data, the patient specific parameters, and a diagnosis suggestion.

17. The system of claim **10**, wherein the memory device further causes the system to:

send raw data of the frequency of the quasi-periodic signal to a hospital information system;
 analyze the raw data at the hospital information system; and
 store results of the analysis at the hospital information system for later review by a medical professional.

18. The system of claim **10**, wherein the memory device further causes the system to:

remove a DC component from the received representation of the quasi-periodic signal to produce a purely time-varying signal, and
 filter, the time-varying signal to produce the pre-processed time-varying signal.

19. The system of claim **10**, wherein the tapering function including a time constant parameter that is a function of the quasi-periodic signal, the memory device further causing the system to:

store the auto-correlation output;
 in response to applying the biphasic tapering function to the auto-correlation output, produce the first maximum; and
 store a representation, based on the first maximum, indicative of the frequency of the quasi-periodic signal.

20. The system of claim **19**, further comprising a portable device, the memory device further causing the system to:

save the representation indicative of the frequency in a file of a predetermined file format;
 send the file in an e-mail;
 print the file; and
 store the file on the portable device.

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[标]申请(专利权)人(译)	SCHRIEFL ANDREAS J REINISCH ANDREAS J		
申请(专利权)人(译)	SCHRIEFL, ANDREAS J. REINISCH, ANDREAS J.		
当前申请(专利权)人(译)	SCHRIEFL, ANDREAS J. REINISCH, ANDREAS J.		
[标]发明人	SCHRIEFL ANDREAS J REINISCH ANDREAS J		
发明人	SCHRIEFL, ANDREAS J. REINISCH, ANDREAS J.		
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摘要(译)

一种系统，包括产生准周期信号电子听诊器，处理器和具有存储指令的存储器设备，当由处理器执行时，使得系统接收准周期信号的表示，以移除DC分量。从接收到的准周期信号的表示产生纯时变信号，并滤波时变信号以产生预处理信号。预处理信号的一部分与其自身自相关，并存储相应的自相关输出。双相锥形函数应用于自相关输出并产生第一最大值，该函数包括作为准周期信号的函数的时间常数参数。基于第一最大值存储表示，作为准周期信号的速率或频率的指示。

