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Photoplethysmogram combined with the Art of Eastern Pulse Analysis: a Novel Way to Assess Body and Mind Energy Balance

Patrick Celka[1*], Marina Brucet[2], Niclas Granqvist[1] and Herbert Schwabl[1]

[1]*SATHeart SA, Rue Galilée 15, CH-1400 Yverdon-les-Bains, Switzerland.*

[2]*Lama Tzong Khapa Institute, Via Poggiberna, 15, I-56040 Pomaia, Santa Luce PI, Italy.*

[*]Correspondence:
Patrick Celka, SATHeart SA, Rue Galilée 15, CH-1400 Yverdon-les-Bains, Switzerland, Email: patrick.celka@satheart.com.

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ABSTRACT

The photoplethysmogram (PPG) is currently used to assess the autonomic nervous system in wearable sensors but the PPG also contains additional information about the arterial system and mental state. This knowledge was known by ancient medicinal system, especially those from the Eastern countries. We present a work that combines the Tibetan medicine concepts of three fundamental energies or humours called Tripa, Lung and Beken with modern techniques of PPG signal analysis to derive a holistic view on the state of a person.

***Aims**: To quantify the state of energy balance of a person using PPG and the three energies. The methodology is further validated in the context of mental stress and active breathing relaxation.*

***Methods and Material**: In Study 1, PPG features were computed on 33 subjects to derive the three energies. In Study 2: The energy balance was derived and validated on ten subjects.*

***Results**: Statistical results show that the PPG derived energies are significantly (Student t-tests) different from baseline in stress and relaxation. Energy balance shows a large group variance and exhibit the well-known psychophysiological adaptation process.*

***Conclusions**: We have demonstrated the potential benefit to use PPG to assess the mental and cardiac and vascular state of a person using Tibetan medicine concepts. The energy balance metric can potentially have great value in the assessment of mental state disorders such as anxiety, stress and depression and applied in the context of breathing based relaxation techniques.*

Keywords

Photoplethysmogram, Tibetan Medicine, Mental stress, Breathing technique.

Key messages

Ancient pulse reading techniques have been translated using a photoplethysmogram signal which can be used as a holistic way to assess people's quality of life balance. Inter-beat intervals have been used to compute features linked with heart rate variability and express a quantitative formula for this life balance.

Introduction

Human body seeks homeostasis and homeodynamic in order to optimize its function like all systems in nature [1-4]. The analogy of homeostasis is when a person tries to keep still standing balance, while homeodynamic is similar to a person seeking balance while walking or running. These processes take place from cells to organs and social networks at different time scale from microseconds in neuronal processes to hours and days in metabolic and circadian rhythms [5]. The term balance is analogous to harmony or coherence in its essence. A state of balance can be achieved when the systems in question are in a state of mutual equilibrium which usually minimize their joint entropy, that is to say increase its orderliness thus increasing a state of inner and outer coherence between its subsystems and with its surrounding and noteworthy in cardiac and brain functions [6,7]. A good example is when two such systems interact and synchronize their states such as the heart rhythms of two persons sleeping close to each other or heart-brain coordination during meditation.[8,9] In fact, many systems in nature exhibit this phenomena including biological ones.[10,11].

The human body has a great capacity to self-adapt to maintain this balance in many circumstances but also is prone to lose it when information given to the organism is either in a state of incoherence or overload its processing capacity such as in stressful situations [12]. Maintaining a state of balance and coherence can be a conscious process, either performed willingly via mental action such as meditation or by using active breathing techniques activating the autonomic nervous system or both [13-17].

The human body is composed of essentially three vital systems for controlling the organ function and optimizing the energy transport and metabolization: 1) the heart and lungs for circulating the blood and oxygen/carbon dioxide management, 2) the autonomic nervous system for optimizing organ functions and 3) the blood constituents and conduits for optimal energy distribution [18]. The conscious and unconscious processes of breathing are primordial in this energy transport and thus in maintaining a stream of vital energy to organs and tissues such as between brain and heart [19].

The state of balance is thus maintained and achieved through these dynamic processes which in turn could be assessed through blood pulse wave analysis techniques. Indeed, the blood pulse wave contains information about the three systems that we mentioned above as well as the breathing patterns [20,21]. Additionally, the blood pulse wave also contains much information about the organs that visited on travelling from the heart to the periphery [22]. The blood pulse wave thus conveys all the information we need to assess a state of balance or imbalance and can be useful in assessing mental stress or distress [23-25].

Balance is very important both for the body and the mind. Our modern era is however subject to many threatening components for this balance. Among the most important are on one side external aspects such as air, electromagnetic, sound and light pollution and on the other side inner aspect of mental stress. The focus of this study is on the second aspect which has serious consequences for health such as high blood pressure, cardiac dysfunctions, immune system weakening and dysautonomia, as well as anxiety, attention deficit and depression [26-29]. All of these being the direct cause to our social and economic situation.

The knowledge of finger pulse reading is known since centuries by many ancient traditions, both Persia-European and Eastern countries [30-36]. Eastern traditions have been kept alive mainly due to geographical and economic reasons. Tapping into this knowledge has thus potentially great value as it contains empirical accumulated holistic knowledge that has been progressively lost in western science to the benefit of analytic and instrumental approaches. The concept of balance is essential in Eastern medicine and contains both physical body and mental aspects. Indeed, the holistic nature of Eastern medicine is strongly reflected by the inseparability of body and mind. Consequently, these medicines seek the source of illnesses both in the body and mind and treat them alike. A state of balance is recognized by the harmony of three basic components: physiological and structural, energetic and mental processes. In particular, Ayurveda and Tibetan medicine defines three types of fundamental humours which when either in excess or deficiency for an individual signifies a state of imbalance and thus a risk of developing illnesses [35,36]. Finger pulse reading is a technique that can diagnose these three humours and thus states of imbalance. From this information these medicinal systems try to rebalance these humours. Every individual possesses his particular typology from birth, that is to say a proportion of these three humours. A state of imbalance is always measured with respect to this typology, which is the reference point for the physician [35,36].

The aim of this work was to fold: 1) to cross-fertilize western modern blood pulse wave measuring instruments and data analysis with ancient finger-based pulse wave analysis in order to tentatively define quantitively an energy balance concept from measured pulse waveforms and 2) to validate our approach on the very specific use case of mental stress and breathing relaxing techniques. Our first study is based on the recording digital pulse waveforms using a photoplethysmograph (PPG) sensor together with an experienced Tibetan physician finger's reading. A statistical analysis further allowed us to interpret and classify the Tibetan pulse diagnosis with the use of our PPG sensor data and further quantified a state of energy balance. This energy balance formula was assessed during the second study using PPG signals.

This work has the potential to empower each individual and therapist with a cost-effective holistic health balance sensing and self-coaching platform.

Subjects and Methods

The paper presents two studies that were conducted in two different countries at different times. The first study was prepared and conducted in Italy between 2008 and 2010 and recordings in November 2010. The purpose of the study was to investigate the use of PPG signals as a tool for analyzing the pulse wave in a similar way as a Tibetan doctor does. The final aim was to develop a PPG-based classification of the three energies. The second study was elaborated and realized at St Thomas Hospital in London in 2018 and was designed for the analysis of the pulse wave during periods of mental stress and relaxation. This second study served as a validation of the first study and additional analysis of the pulse wave harmonics.

Both studies conform to the seventh declaration of Helsinki (2013) on ethical principles regarding human experimentation developed for the medical community by the World Medical Association

(WMA). Informed consents were signed and dated by each participant of both studies.

Study 1: Digital Tibetan Pulse Reading

Tibetan medicine makes use of three humous or energies known as: Phlegm (Tibetan: Beken), Wind/Air (Tibetan: Lung), and Bile (Tibetan: Tripa). These three energies originate from Ayurveda, the Indian Traditional Medicinal system [35,36]. Each of these humors have both physical and mental aspects. Beken is associated with our foundational structure: bones and marrow, flesh and liquids. Beken has the mental quality of calmness and focus. Lung is linked to movements: nervous system activity, blood flow and physical movement. Lung is linked with thinking processes and emotions. Tripa has the feature of heat and thus with metabolic processes. Tripa is linked as well with our sense perception and mental clarity.

The exceptional discovery by ancient physicians that the pulse wave characteristics can be mapped to the three energies led to great progresses in the art of diagnosis. Tibetan medicine qualifies the pulse wave using a descriptive method with lots of analogies of animal features and behaviors. Certain qualities of the pulse are more prominent at certain locations of the bodies but in most cases, the radial artery is used by the doctor. The traditional doctor position three fingers (index, middle and ring) alongside the artery on each wrist to perform the diagnosis using various pressure levels on the fingers. Figure 2 illustrates the finger position.

It is nowadays well known from digital pulse wave analysis that the pulse waveform varies depending on the body location and contains information about the organs and tissues 'visited' by the travelling wave from the heart to the periphery. Additionally, research started to appear on the effect of mental processes and emotions using features contained in the pulse wave which correlates with the Tibetan medicine and Ayurveric approaches. The pulse wave dynamic has three aspects that we call principles: Rhythm (Quick, slow, fast, rolling and intermittent, (in) coherent), Force (Sunken, strong, empty and weak) and Complexity (Rough, sharp). These three qualitative principles can be quantified using signal processing terminologies with the following physiological interpretation:

Rhythm: is the way the heartbeat intervals are distributed, fast or slow as a manifestation of the autonomic nervous system activity. This quality can be reasonably well described using heart rate (*HR*), heart rate variability (HRV) and breathing frequency. In this study, we have used the two first parameters with the HRV measured by the root mean square of the successive inter-beat intervals difference (*RMSSD*) [37].

Force: is the strength of the blood pressure felt under the fingers. Our PPG sensors capture the changes in blood oxygenated red cell volumes and vessel diameter at each heartbeat. The peak-to-peak amplitude of the PPG signal is thus an indirect measure of the relative blood pressure. This aspect has not been taken into account in this study due to the fact that the PPG signal can change amplitude according to the pressure to the skin which is in most practical cases uncontrollable when not in a clinical setting with specialized equipment.

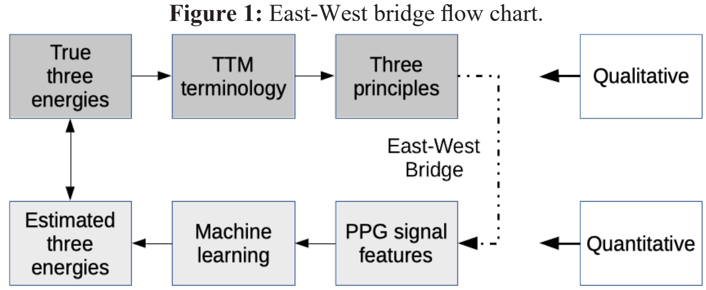
Complexity: is either the contour of the pressure wave shape or the regularity of the heart inter-beat intervals. The pulse wave contour characteristic can be related to local vasoconstriction and/or dilation of the vessels as well as the arterial branching system which influences the location of the dicrotic notch, the time from the foot of the systole to its peak amplitude also known as the crest time as well as the amplitude of the dicrotic wave. The shape of the pulse wave can have low, average or high complexity. In this study, we only made use of a cardiac coherence index (*CCI*). The quantitative pulse wave parameters are thus: *CCI*, *HR and RMSSD*. Table 1 shows a qualitative interpretation of the three energies (Tripa, Lung and Beken) in function of the two dynamical aspects (Rhythm and Complexity).

	Beken	Lung	Tripa
Rhythm	Low, variable	Average, variable	High, stable
Complexity	Low	High	Average

Table 1: Qualitative relationship between the three energies and principles.

The qualitative interpretation from Table 1 must be translated into quantitative one using signal processing and statistical techniques. The complete flow chart of our work is shown in Figure 1 where we clearly distinguish the TTM qualitative path (Traditional Eastern medicine) and the digital pulse wave analysis path (Technological Western medicine). The true three energies are diagnosed by the Tibetan physician, while the estimated ones are those derived from our algorithm.

Figure 1: East-West bridge flow chart.



Subjects

The subject pool consisted in 34 healthy participants (between 18 and 65 years of age, Male (13), Female (21)) engaged in studies at the Lama Tzong Khapa (Pomaia, Italy). Each participant gave an informed consent to this study and received an identification code (ID) to preserve privacy, and data from each subject was kept anonymously. This ID is used to identify the doctor assessment sheets, pulse wave recordings and clinical measurements. Amongst the 34 subjects, we have the following fairly equally distributed typology: Lung (14), Tripa (8) and Beken (12). The inclusion criteria were as follows: Healthy subjects, having a relation with the Institute Lama Tzong Khapa and/or living in the residential area close by, and willing to be enrolled for the entire duration of this study. Physical and mental health was ascertained by the medical doctor and psychologist in charge of this project. Exclusion criteria were as follows: Hypertension level 2 (Systolic >160*mmHg* and/or Diastolic > 95*mmHg* without medication), Cardiovascular problems, Cancer, Diabetes, Breathing disorders, Mental illness such as schizophrenia, phobias, etc. Subject 1 (Lung) was excluded from the study because of signs of hypertension. Participants were given clinical advice after the study period, so that they are compensated for having participated in the study.

Protocol

At the time of the enrolment, participants were asked to complete a questionnaire with their background relevant data, such as age, gender, height and weight which was anonymized. According to Tibetan Medicine, the typology assessment requires the medical doctor and the patient to respect certain rules such as: diet and behavior the day before the reading and the time of the day which is traditionally early morning or at dawn when the outer and inner elements are the most balanced. Due to logistical constrains and the number of participants, we had to adapt these traditional rules by relaxing the time of day. The Tibetan doctor can slightly adjust his pulse diagnosis according to the time of when the assessment is done. The participants were asked to behave calmly and avoid eating spicy food and excitants the day prior to the recording. Routine subject information was recorded and done continuously during the study. When the participants visited the Tibetan doctor, they had a Tibetan pulse reading, which was immediately followed by our pulse wave sensor recording. The total recording session were 30 minutes: 15 minutes for the Tibetan finger pulse reading and three to five minutes for the digital pulse wave recording. We used such a short recording time in order to avoid muscle tension, movement and sweating artefacts as much as possible.

Physiological measurements: blood pressure and heart rate were measured using a medical grade automatic commercial oscillometric system (Omron IA2, Kyoto, Japan).

Self-report: participants were asked to regularly fill a multiple-choice report on temporary non-compliance, exercise, personal meditation practice, diet, work or study load.

Method

The PPG Sensor

The Tibetan pulse information can be measured sequentially with one finger at a time as well as simultaneously with the three fingers and is traditionally assessed by the fingers' feeling of the doctor, placed along the radial artery. Left and right wrist pulse reading were taken.

Measurements performed by our pulse wave recording system rely on the photoplethysmogram (PPG). PPG is an optical non-invasive technology allowing the assessment of information related to subcutaneous blood circulation [38]. By illuminating a living tissue with a light source, PPG can measure both arterial blood volume changes and blood content. PPG measurements setups consist in a light source, a photodiode and the electronics for signal conditioning and filtering. Our optical probe included a Light Emitting Diode (LED) emitting at 940*nm*, and a photodiode located 10*mm* apart. The electronic box includes an analog front-end (performing the continuous removal of ambient light reaching the photodiode and acquiring the raw optical signals 32 times per second (sampling frequency *Fs* = 32*Hz*) via a 24 bits Analog to Digital Convertor). Raw optical signals were transmitted via an USB cable to a laptop where data were displayed and stored for further processing. The PPG signal was oversampled to 50*Hz* for analysis. Left and right wrist PPG signals were recorded sequentially. Both data were used in our analysis to derive the *CCI*, *HR*, *RMSSD* parameters.

The sensor was made for single finger position measurement at a time and we used the index finger position. The index finger location is the one proximal to the thumb as can be seen in Figure 2. The sensor was then positioned on the radial artery in a similar way a Tibetan doctor would sense the pulse until the signal showed some stability as displayed on the screen of the computer. Once an optimal position was found, the sensor was maintained with a wrist band during the duration of the recording. Transient data at the beginning and end of each recording were discarded due to large artefact. 60 seconds of PPG data were used for analysis. PPG signals amplitude and sensitive to the pressure applied to the sensor. This forbids us to use the Force principle as our system did not allowed for pressure calibration. The PPG signals were analyzed off-line using Matlab © software (Math Works, Inc., Natick, Massachusetts, United States).

The digital processing

Inter-beat interval detection

A peak detection algorithm was used to detect each diastolic point $P(m)$ from DPW (t) at the heartbeat m, and then derive the inter-beat intervals $PP(m) = P(m) - P(m-1)$. The detection algorithm consists in three steps: a Butterworth 4th order band-pass filter with cutoff frequencies 0.3*Hz* and 3*Hz* followed by a first order derivative filter and an adaptive peak detection method [39]. This relatively narrow bandwidth was purposely designed to optimize the heartbeat intervals detection as they are the base for our algorithm. The Butterworth filter removed most of the high and low frequency noise. The slope of the DPW (t) during the systole phase is characteristically high which results in a sharp peaked signal DPWFD (t) after the derivative. The adaptive peak detection method described in was used to finally find the peaks of DPWFD (t). Spline interpolation around the detected peaks was used to increase the peaks location accuracy. We have used a technique to automatically detect and eventually correct non-physiological PP intervals or ectopic beats [40].

Heart rate variability indices

Each energy E: $E_1 = Tripa$, $E_2 = Lung$ and $E_3 = Beken$ have qualities according to Table 1 which are hypothesized to be reflected in physiological parameters derived from the $PP(m)$

data. For each E_j, three parameters P_{1j}, P_{2j} and P_{3j} were computed from the inter-beat intervals $PP(m)$: 1) the cardiac coherence index ($P_{1j} = CCI$), 2) the heart rate ($P_{2j} = HR$), and 3) the heart rate variability measured with the root mean square sum of the differences ($P_{3j} = RMSSD$).

From an inter-beat interval signal $PP(m)$, the parameters P_{ij} were computed from $N = 3$ successive indexed segments T_k; $(k = 1, \dots, N)$ of 30 seconds PP overlapping each other by 15 seconds. The number of values P_{ij} per subject was thus $N = 3$ values per recording for each wrist and parameter: i.e. six values for each parameter per subject. We thus have accumulated for each parameter: 84 values for Lung types, 48 values for Tripa types and 72 values for Beken types. We then generated 1000 surrogate data for each parameter in order to increase the robustness of our statistical analysis [41]. This surrogate method conserved the probability density function as well as the frequency spectrum (phase and amplitude) of the original data.

While the two indices *HR* and *RMSSD* are well described in the literature, the cardiac coherence index is new, and we present here a brief overview of its derivation. The *CCI* is based on the two complimentary concepts of cardiac coherence and autonomic nervous system resonance [14,42,43,63]. Resonance and coherence are often mistakenly interpreted as equivalent but are however different phenomena that needs to accounted for separately. While resonance manifest as the increase of amplitude of a certain variable common to coupled or forced systems, coherence is related to the common dynamic behavior between systems or within a system states [6,7]. Coherence and resonance can however co-exist in that is called coherent resonance [7].

In addition to the heart rate, the $PP(m)$ variability is important for maintain a state of balance and optimal energy usage. We often hear the term coherent speech, coherent light or coherent quantum states. Systems and signals can be defined as being in a coherent state if they manifest a high degree of orderliness or low entropy [10]. Heart rate variability is no exception whereby heart inter-beat intervals regularity is quantified using entropy [44]. On each segment T_k, we computed the normalized power spectral density S_k in the frequency band 0.04*Hz* to 0.3*Hz* and then estimated the normalized spectral entropy H_k [45]. Our definition of the cardiac coherence is as follows:

$$H_k = 1 - G \sum_{n=1,..,B} S_k(n) \log_{10}(S_k(n)),$$

Where G a normalizing is factor so that H_k is bounded between zero (lowest entropy, maximum order) and one (maximal entropy, lowest order); S_k is the normalized power spectral density of the $PP(m)$ intervals in segment T_k, and B is the number of frequency bins used for estimating S_k. The *CCI* is further weighted by a function $W(f_k^c, f^r)$ to account for the breathing frequency f_k^c and its distance from the resonant frequency $f^r = 0.1Hz$. The function W is one if the breathing frequency is equal to the resonant frequency and decreases otherwise. A typical weighting function is:

$$W(f, f_r) = 1 - \left|\frac{f - f^c}{f^r - f^c}\right|$$

The resulting cardiac coherence index CCI_k is expressed as:

$$\mathrm{CCI}_k(f^r) = \sqrt{W(f_k^c, f^r)\,(1 - H_k)}$$

The interpretation of the *CCI* is as follows: a value of the *CCI* close to unity indicates that the $PP(m)$ intervals have low entropy (H_k close to zero) and that their rhythm is close to the resonance (W close to one). While the resonant frequency is subject dependent and varies in the vicinity of 0.1*Hz*, we have assumed this frequency fixed to 0.1*Hz* for all subjects in this work.

Computation of the three energies

For sake of comparing different subjects of different age and gender, we have normalized the $P_{2j} = HR$ and $P_{3j} = RMSSD$ between zero and one following the age and gender dependencies of these parameters. The resulting normalized parameters *HRn* and *HRVn* were called N_{ij}. We estimated a probability function f_{ij} and found the 5%, 10%, 90% and 95% percentile statistics of N_{ij}: Q_{05}, Q_{10}, Q_{90} and Q_{95} respectively. For each metric and energy N_{ij}; $(i, j = 1, \dots, 3)$, we associate a fuzzy energy membership function $0 \le M_{ij} \le 1$ which is a piecewise linear function constructed from Q_{05} to Q_{95}, an illustration of which is shown in Figure 2.

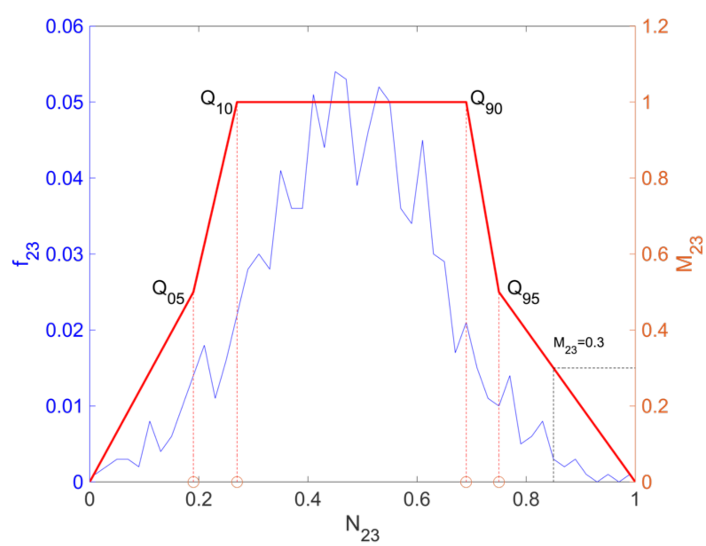


Figure 2: Example of membership function M_{23} (red) associated with the probability density function f_{23} (blue) of variable N_{23}, together with the percentile Q_{05} to Q_{95}.

We thus have 3 x 3 membership functions M_{ij} corresponding to the three energies E_j and three parameters P_{ij}. For example, if the Figure 2 is for $E_3 = Beken$ and for the heart rate parameter P_{23} with *HR*=100 beat per minute and normalized value $N_{23} = 0.85$ The likelihood of N_{23} is $M_{23} = 0.3$, meaning that a Beken person is unlikely to have such a high heart rate at rest. All energies will have different Q_{05} to Q_{95} and thus membership functions. The Result section gives our estimated values for our database as well as a complete illustration of the different membership functions for each energy.

Each energy E_j has likelihood L_j depending on each value of M_{ij} for all normalized physiological parameter N_{ij} expressed by the product of M_{ij} for all i as follows:
$L_j = \prod_{i=1}^{3} M_{ij}$.

For example, the likelihood of a person to be Tripa is $L_2 = M_{12} \times M_{22} \times M_{32}$, that is he must have all values of M_{i2} quite high.

Energy balance formula

Each individual possesses a certain proportion of Lung, Tripa and Beken. The original Tibetan medicine text talks about seven different types which are obtained simply by combining all three energies. However, our method enables us to have a wide spectrum of energies as each L_j can take any value between zero and one. Our assessment method provides us with a triplet vector $L = (L_1, L_2, L_3)$ which when sorted by decreasing values gives the energy dominance for this person at the time of measurement. For example, a Tripa dominant person with a bit of Lung and few Beken will have $L_2 > L_1 > L_3$. As we have pointed out in the introduction, each person will have a specific energy type from birth, which evolves slowly along the lifespan. This specific energy is called the typology that we will call reference energy (L^R) and is the reference energy point for this person. This reference energy is traditionally assessed by the Tibetan doctor at certain epoch of the year following a very specific protocol.

In Tibetan medicine, the concept of balance is essential and in particular energy balance (B). A state of balance at a certain time t means that this person's energy $L(t)$ is close to his reference energy vector L^R. Thus, the reference energy plays an essential role in assessing the health of a person and moreover it means that certain physiological conditions for a person might represent a balance state, while it might be totally imbalance for another person with different reference energy. These ancient medicinal systems are thus holistic in the sense that they assess the health of the complete body as well as the mental state, and they are individual as each assessment of balance depends on the reference energy of this person. The energy balance measured by our method at a time t is expressed by the following equation:

$$B(t) = \sum_{i=1}^{3} (w_i L_i(t) - L_i^R/3)$$

Where the weighting factors w_i are usually 1/3 but can be adapted according to the season and time of the day following the constrain that their sum is equal to one. Indeed, Tibetan medicine tells us that each season and time of day has its own tendency to increase a type of energy. For example, summer increases Tripa and winter increases Beken; midday is likely to increase Tripa while sleep increases Beken. $B(t)$ Is bounded between one and minus one, whereby positive and negative values indicate either an excess or deficiency in some of the energies E_j. The energy balance $B(t)$ can be considered as a health index as opposed to a stress index which would include only the positive sides of$B(t)$.

Study 2: Mental Stress

The mental stress protocol has been presented in detail in Celka et al. and is briefly reproduced here [22].

Subjects

Ten young, healthy participants (4 males and 6 females, age range 23 – 31 year of age, Body Mass Index range 17.6 – 33.8 kg/m^2) participated in the study at St Thomas' Hospital, London. All participants completed a preliminary questionnaire about cardiovascular and mental health as well as any medications that could influence the results. Exclusion criteria were: diagnosed hypertension, heart arrhythmias and cognitive impairments. The NRES Committee London – Westminster approved the study IRAS ID (168545) and REC reference (15/LO/1173). Participants could ask to withdraw or pause at any time during the study. Subjects received an ID code to preserve anonymity.

Protocol

The study protocol consisted of six phases as illustrated in Figure 3 instrumentation, baseline measurements, Strop test 1, relaxation phase, Strop test 2, and recovery. Blood pressure (BP) measurements and subjective stress assessment using a visual analog scale (VAS) were performed before and after each protocol phase. The study was conducted in a dedicated room, isolated from noise and other visual disturbances. The study phases are described next. During the Instrumentation phase, participants were provided with instructions on how to perform the Stroop test and relaxation phases, and measurement instruments were attached (as explained in the next section). As part of the routine clinical protocol at the hospital, participants completed the Patient Health Questionnaire (PHQ-9).

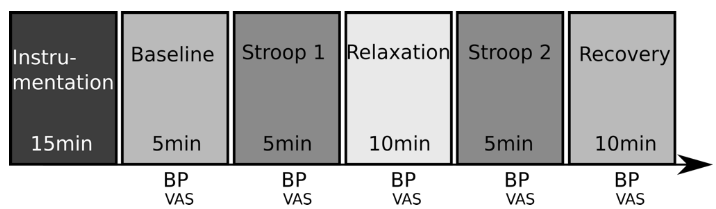


Figure 3: The five phases of the study protocol and their duration.

The Baseline phase, consisted of acquiring measurements from participants whilst lying on a bed, head tilted up slightly, for five minutes whilst breathing spontaneously. In the Stroop test 1 phase, stress was induced using the color word Stroop test. This test has been shown to provide reasonable results in terms of controlled induced stress and is widely used in psychology research. The test was performed for five minutes while subjects were lying down in the bed looking at a computer screen where the Stroop test was running. Participants were asked to answer simple word-color-matching questions, at an increasingly faster pace as the test progressed to compensate for the known adaptation process that participants undergo. In the Relaxation phase, participants used the RESPeRATE system (RESPeRATE ©, Newark, USA) for ten minutes, which is designed to lower blood pressure through device-guided slow-paced breathing. The breathing frequency range was adjusted for each individual according to his comfort zone during the instrumentation of the subject prior to the start of the protocol. In the Stroop test 2 phase, a second Stroop test was conducted lasting five minutes. In the Recovery phase, participants relaxed, unaided and in silence, for ten minutes whilst isolated by a curtain. Reference assessments of stress were obtained at the end of each phase by asking participants two questions: (i) do you feel any pain or discomfort? And (ii) how would you rate your stress level? Subjects provided responses using a VAS ranging from zero to ten. The VAS has been successfully used in many psychological studies and has the great advantage of being very simple, especially during experiments when subjects are psychologically stressed.

Method

PPG signals for pulse wave analysis were acquired using OH1 sensors (Polar Electro Oy) placed on the lateral site of the left upper arm. The OH1 device complies with electro-magnetic radiation safety, has been tested for skin biocompatibility. The OH1 sensor consists of a hexagonal arrangement of green light sources and measures PPG signals at 135*Hz*. The digitalized PPG signal was further band passed filtered with a linear 4th order Butterworth filter with cutoff frequencies 0.2*Hz* - 15*Hz*.

Results

Study 1: General subjects' physiological conditions

Tibetan and Ayurveda medicines provide insights into the heart rate and blood pressure according to typology: 1) Tripa: rather high blood pressure and heart rate, 2) Beken: rather low blood pressure and heart rate, 3) Lung, rather average blood pressure and heart rate. Figure 4 shows the systolic, diastolic and amplitude of blood pressure and heart rate average and standard distribution by typology. Our data shows that Tripa and Lung have a quite similar average systole, while Beken has a lower one; Tripa average diastole is higher than Lung and Beken. Average blood pressure amplitude (Delta BP: systole – diastole) shows that Lung as the highest value followed by Beken and Tripa. The Heart rate of Tripa is the highest followed by Lung and Beken. Tripa shows a quite stable systole and diastole across the group; while Beken shows the lowest Delta BP. Beken and Lung have the highest group systole, diastole and heart rate standard deviation, while Tripa typology is the most consistent with the lowest standard deviation. These results are quite in agreement with Tibetan and Ayurvedic literature.

Statistics for the normalized parameters

Quartile statistics of the parameters N_{ij} from our database for all subjects is displayed in Figure 5. The *CCI* index is globally increasing as we inspect N_{1j}; $(j = 1,2,3)$: i.e. Tripa, Lung and Beken. The *CCI* index shows the smaller variance for Tripa people while the larger for Lung people. The *CCI* has the greater average value for Beken. Concerning the normalized heart rate $N_{2j} = HRn$, we observe that Tripa population has the smaller variance as compared to both Lung and Beken. Tripa and Lung population have on average the same N_{2j}, while Beken has the smallest average value. The normalized heart rate variability parameter $N_{3j} = HRVn$ shows a decreasing global trend for Tripa, Lung and Beken respectively, and a larger variance for the Lung population.

Membership functions

The 9 membership functions M_{ij} corresponding to the smoothed normalized probability distributions f_{ij} are shown in Figure 6(a). The graphs on the left panels of Figure 6(a) are the f_{ij} correspond

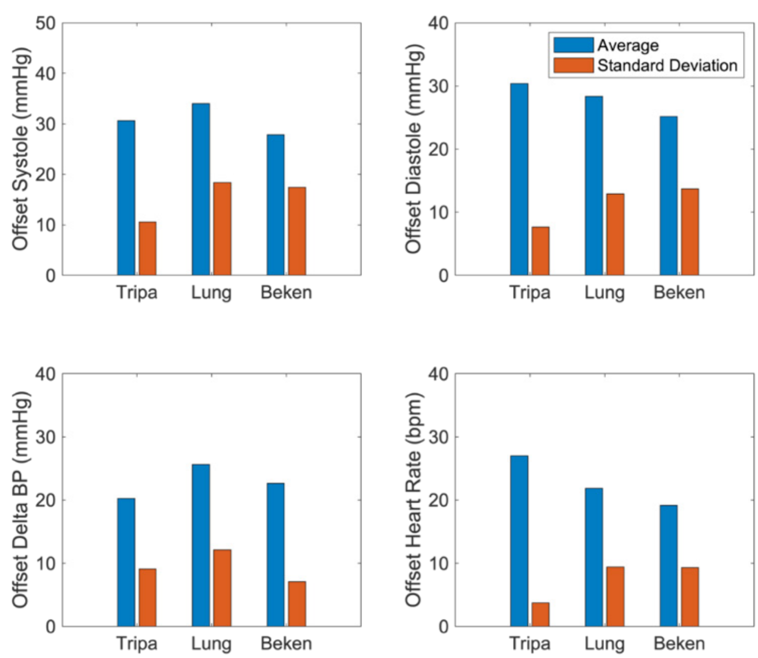


Figure 4: Group average and standard deviation of blood pressures and heart rate.

to the quartile representation of Figure 5 and the membership functions M_{ij} have been derived from f_{ij} following the procedure described above. The functions M_{ij} show how the different energies can eventually be distinguished from each other using our three normalized parameters N_{ij}. Figure 6(b) shows how the distributions f_{ij} overlap for each normalized parameter N_{ij}. We can clearly identify that Beken energy is easily separable from the two other ones, but Tripa and Lung shares a lot, especially for N_{2j} which is the normalized heart rate. Tripa and Lung are mostly different from their $N_{1j} = CCI$ parameter.

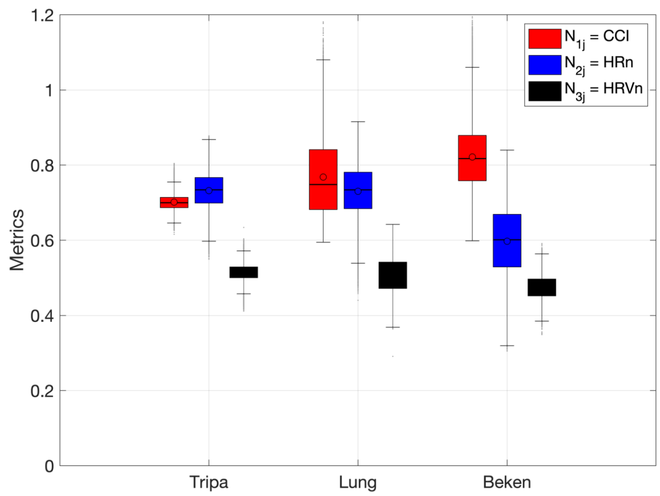
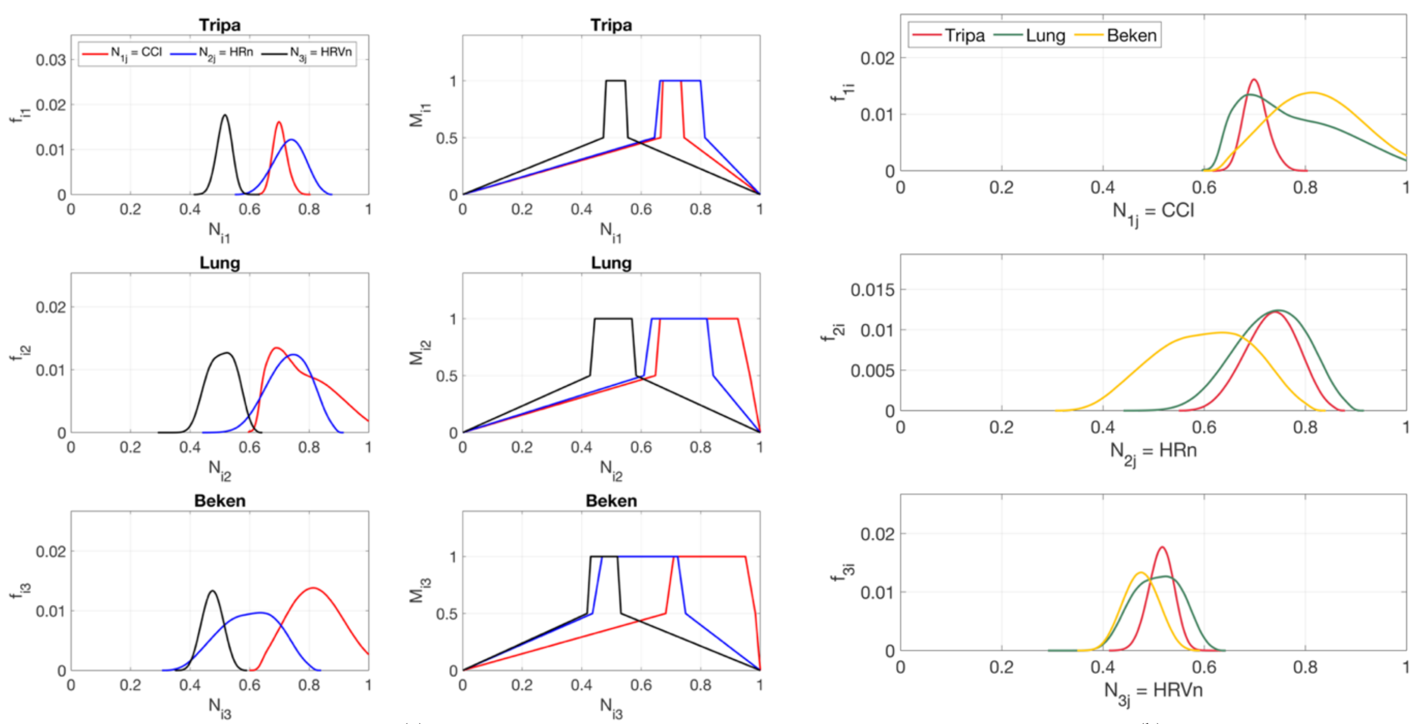


Figure 5: The statistical distributions of the three normalized parameters N_{ij} for each energy Tripa, Lung and Beken.

One way to interpret the different parameter distributions in in Figure 6(a) for each energy is through the coupling between the parameters. Indeed, the coupling can be viewed under the Bayesian approach of system inference whereby the probability distribution of the states of the system can be inferred via Bayes's theory and the coupling identified with the conditional probabilities of the various states [46]. The overlapping between different parameter distribution is proportional to the coupling between them, that is to say the way each other interacts. The larger the overlapping the greater will be the coupling. That means for example that for Tripa energy, the coupling between *HRn* and *CCI* is quite significant, while the coupling between *HRVn* and *HRn* or *CCI* is almost non-existent. This has implications in terms of the understanding of the mechanism governing the physiological processes involved in each type of energies.

The distributions f_{ij} have different characteristics: 1) the *CCI* tend to be highly skewed for Lung, highly localized with larger kurtosis for Tripa while Beken shows a small kurtosis with a broad distribution; 2) the *HRn* shows a quite Gaussian shape for all energies, and 3) *HRVn* shows a concentrated distribution for Tripa and a broader one for Lung.

Figure 6 shows that Lung and Beken people tend to have a higher *CCI* as compared with Tripa and that Tripa and Lung share a same *CCI* 'zone' centered around *CCI* = 0.7. The *HRn* of Tripa and Lung significantly overlap, while Beken shows marked lower and broader values as compared with the two other energies. The density f_{23} seems composed of multiple underlying distributions



(a) (b)

Figure 6: (a) The probability function f_{ij} and the membership functions M_{ij} grouped by energy; (b) the same as (a) but grouped by parameters.

one of which is shared with f_{21}. The *HRVn* parameter has the lowest values for Beken, and Tripa and Lung have a shared space with Lung distribution broader than Tripa. Also, we observe that f_{32} seems to have two separate underlying distributions one of which has this shared space with f_{31}.

Study 2

Qualitative behaviour of the three energies and balance

Figure 7 and Figure 8 show examples of the normalized parameters, the energies and the energy balance dynamic across the mental stress protocol for two subjects. For the subject 1 in Figure 7, the three energies Tripa, Lung and Beken show significant response to the stress 1 protocol between 1000 and 1300 seconds. Tripa energy is clearly maximum during this phase, while Lung shows first a decrease followed by a strong increase towards the end of the stress. The relaxation protocol between 1500 and 2000 seconds also provoked a significant response, reducing Tripa and Lung while increasing Beken with a stronger effect towards the end of the relaxation when the breathing frequency is the lowest and close to the resonance frequency at 6 breaths per minutes. Stress 2 shows a much damper response as compared to Stress 1. The Recovery period showed a lower *HRn* as compared with baseline. The *CCI* showed a slow decrease from Stress 2 to Recovery.

The energy balance was computed assuming that all subjects had a reference state, i.e. their typology, in a balanced state $L^R = (0.5, 0.5, 0.5)$. We took this choice because in this study we did not had access to a Tibetan doctor to determine L^R for each individual. We have thus to analyze the energy balance data as relative trends and not absolute values. The energy balance shows almost random slow fluctuations around the zero level prior to dropping below zero during the relaxation and slowly coming back to zero towards the end of the protocol.

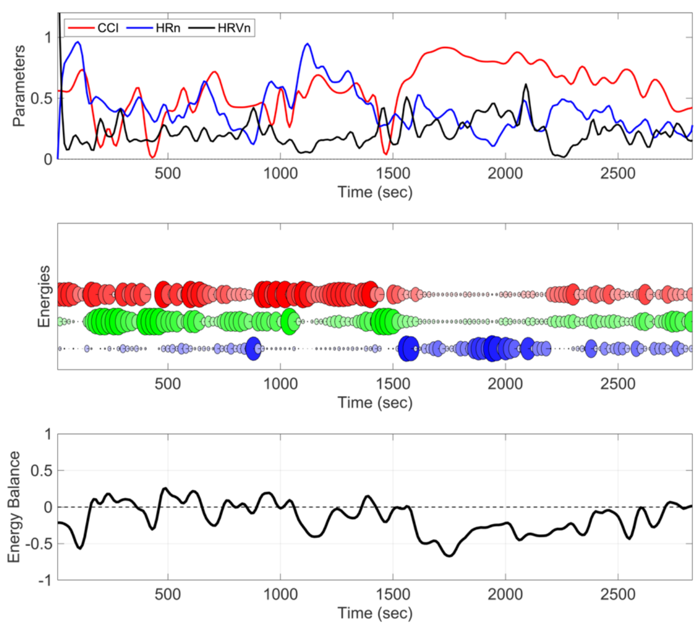


Figure 7: Normalized parameters (upper panel), Energies (middle panel) and Energy balance (bottom panel) for subject 1.

For the subject 10 in Figure 8, the normalized parameters show an almost flat response to either stress or relaxation, with only a significant increase of *HRn* during Stress 1 between 1300 and 1600 seconds. In this period, Tripa and Lung increase while Beken was suppressed. The *CCI* showed also a quite flat curve slightly lowering towards the end of the protocol.

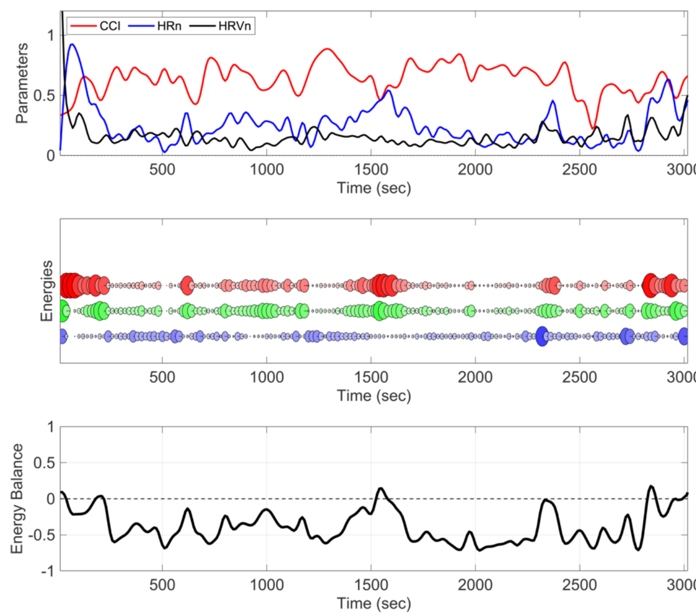


Figure 8: Normalized parameters (upper panel), Energies (middle panel) and Energy balance (bottom panel) for subject 10.

These particular subjects showed a quite relax state from the beginning to the end of the recording with a negative energy balance with a minimum reached during the relaxation protocol.

Statistics on the mental stress and relaxation: validation of our concepts

Figure 9 shows the group statistics for each phase of the protocol of the three energies. Statistical significance is reached for Tripa, between Baseline and Stroop 1 ($p=0.00019$); Stroop 1 and Stroop 2 ($p = 0.0035$) and Stroop1 and Recovery ($p=0.00099$). For Lung, statistical significance is reached between Baseline and Stroop 1 ($p=0.018$), Stroop 1 and Relaxation ($p=0.017$), Stroop 1 and Stroop 2 ($p=0.0099$) and Stroop 1 and Recovery ($p=0.0025$). Lung and Tripa displays rapid changes during the first stress test and rapid decrease during the relaxation protocol, while shows a slow decrease during the two last phases of the protocol. The second stress seemed to have no effect on any of the three energies.

Beken energy shows a trend toward lowering during the Stress 1 compared to the Baseline and increases during the Relaxation as compared to the Stroop 1 but did not reached statistical significance. Stroop 2 shows a large variance similar to Baseline. Recovery stays around the same values as Baseline and Stroop 2. Beken energy thus demonstrates a larger resistance to change as compared with Lung and Tripa which are faster moving energies.

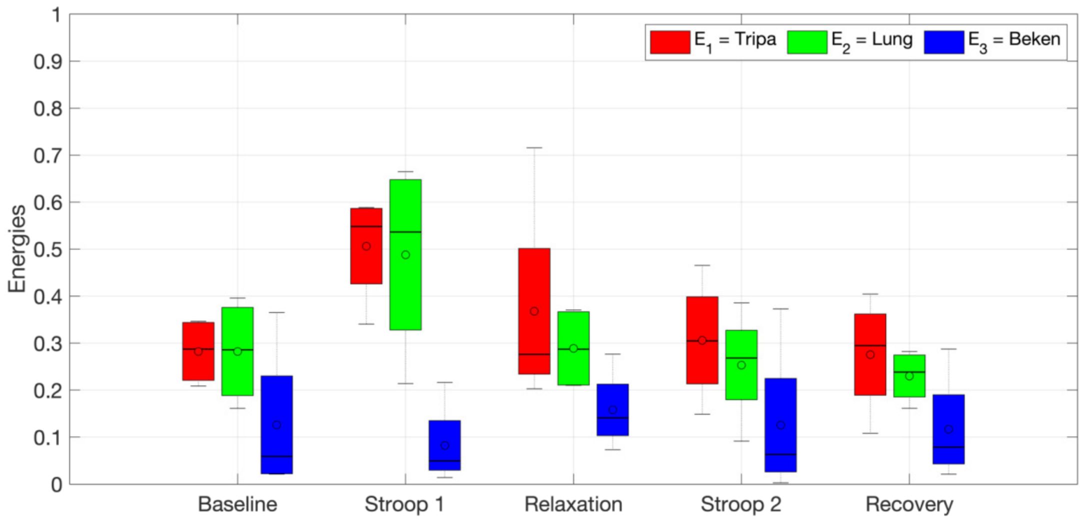


Figure 9: Group average statistics of the three energies Tripa, Lung and Beken during the 5 protocol phases.

The remarkable resistance to change for all energies after the Stroop 2 test is referred to as the adaptation phenomenon which illustrates our capacity to learn and adapt to changes: i.e. the 'surprise' effect of the first stress has been assimilated by our organism. Our organism has thus the capacity to adapt quickly to a just-learned experience. This effect has already been reported in the acute mental stress study by Vlachopoulos et al. whereby they analyse the behaviour of various indices of arterial stiffness and blood pressure [47].

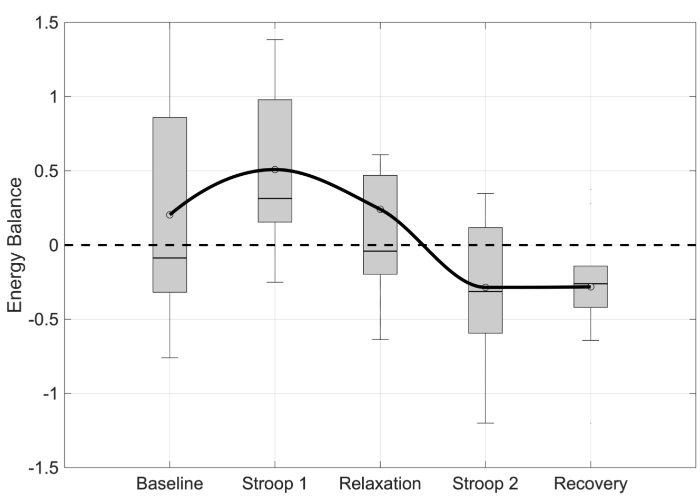


Figure 10: Energy balance group statistics.

Figure 10 shows the group statistics of the energy balance. We recall the reader that this analysis must be viewed in terms of relative dynamics. The black line joins the average of the energy balance for each protocol phase. This curve shows that on average, the energy balance is rising from Baseline and reaches a maximum during Stress 1, drops during Relaxation, drops again during Stroop 2 and reaches a minimum in Recovery. The Figure 10 also shows that the group distribution (standard deviation) of the energy balance for each phase protocol is essentially the same except for the Recovery. Both of these observations tell us that despite the larger fluctuations of the individual energies, Tripa, Lung and Beken, the balance state of these energies varies slowly as if it had inertia. This particular observation will be addressed in the discussion section.

Discussion

In ancient times the world and human body was considered as part of a single whole entity. This was often called the macrocosms and microcosms. The philosophy behind this was based on thousands of years of empirical knowledge. At the four quadrants of the planet, each culture developed his own specific system, but all were based on the knowledge of few principles encapsulated in the four elements. These elements were the base for understanding both the laws of the cosmos and the human body. Medicine was not different, and sickness was thought to be the consequence of imbalance of these elements, either in the cosmos or the body itself. Additionally, it was always assumed that spirit was an integral part of this system viewing mind and matter as component of the *unus mundus*, meaning one world, as recalled by the psychologist Carl Jung and physicist Wolfgang Pauli [47]. Science and medicine are rediscovering these principles and noteworthily in physics, neuroscience and neuropsychology. The dualistic view of human separated from its environment and mind separated from matter is becoming untenable when one takes the scientific approach seriously [48].

Our work presented in this article is based on this ancient knowledge and in particular those conserved to-day by Chinese, Tibetan and Ayurvedic medical systems but also known throughout Europe and Persia. Heart pulse wave analysis is at the core of these medicinal diagnosis systems. It thus comes as no surprise that, when scrutinized by a Tibetan physician, the pulse rhythm, force and structure reflect the three aspects of the human body, its environment, and the mind. The pulse wave is thus a treasure of information for the physician and we have investigated the possibilities to map these ancient methods using modern sensing and processing techniques. Our results show that there are evidences that such a correspondence is possible, even from a simple analysis of the pulse rhythm. The rhythm is only one component of the pulse diagnosis assessment, but it is readily available at low cost for any accurate heart rhythm sensor such as an electrocardiogram or the blood pulse wave [38,39,49]. Our work is focused on the blood pressure pulse wave as measured by the photoplethysmogram, which is a signal reflecting blood volume and arteries changes, as one of the goals is to embed our methodology in user friendly wearable or portable device for self-assessment and coaching [39].

Our first study was designed to create this first map between Tibetan pulse diagnosis and the photoplethysmogram. Three fundamental energies derive from the elements as described in Tibetan and Ayurveda medicine and called Tripa/Pitta, Lung/Vata and Beken/Kapha respectively [35,36]. These energies determine what is called the typology as an essential feature of each individual from birth and evolves slowly throughout the life [35,36]. The three energies were estimated from our digital analysis using three heart pulse rhythm parameters, namely: a measure of self-coherence or order called cardiac coherence index, the pulse rate and the heart rate variability (or more precisely inter-beat intervals variability). The cardiac coherence index is especially linked to the activity and regularity of the autonomic nervous system flow in the breathing frequency range [14,50]. The heart rate variability is a measure of the amplitude and distribution of the fluctuations of the inter-beat intervals, and the heart rate is the integration and main output of the cardiac and vascular function, both sympathetic and parasympathetic, blood pressure and breathing regulation. Our results show that the three energies are not independent from each other as shown in the distribution on the left side of Figure 6 similar to Tibetan medicine where they are described as embedded into each other. However, we have noticed specific behaviours: Tripa population shows a more concentrated distribution of all three parameters, and especially the coherence index, showing high consistency of physiological dynamic and mindset of these types, especially viewed from the heart rhythm. Lung types have generally broader distributions as compared with Tripa with skewed coherence index towards high values and rather high heart rate and medium broad heart rate variability. Lung types are characterized by agility and movement both from a physiology and mental aspects which are well reflected by our analysis. Beken people have broad heart rate and coherence distribution with an average heart rate which is the lowest of all three types. Average heart rate variability is the lowest of all three types with a well concentrated distribution. Beken types have the features to be calm and have slow and stable physiology and mind. This is again well reflected by our analysis.

An important aspect of our analysis is the coupling effect between the different parameters *CCI*, *HRn* and *HRVn*. The coupling phenomenon in the cardiac rhythm, autonomic nervous system and blood flow has been well studied demonstrating the nonlinear interactions between the central and peripheral control mechanisms [50]. However, the coupling of *CCI* and *HRn*/*HRVn* is clearly revealed in our stress study. The meaning of this coupling can be linked to the coupling between the heart rhythm respiratory rhythmic components and other rhythms at lower frequencies further illustrating the nonlinear nature of the physiological system [51]. Moreover, thanks to our Eastern interpretation of the energies, we can also infer a similar nonlinear coupled dynamical behaviour present in most natural systems [52].

From these statistical population parameter distributions, we constructed mathematical expression of the likelihood of each energy as shown on the right part of Figure 6. This allowed us in a second study to analyse dynamics of the energies of subjects under mental stress and breathing relaxation. We observed that during mental stress both Tripa and Lung were activated and showed a sharp increase, while Beken was suppressed. This resulted in an upward shift of the energy balance. The relaxation phase on the other side proved to decrease Lung and Tripa and increase Beken, which resulted in shifting down the energy balance. The rest of the protocol showed non-significant changes with respect to previous states and the energy balance came back close to the baseline condition. The black curve in Figure 10 look like the response of a damped harmonic oscillator to a kick which is in our study simulated by the mental stress. This dynamic process reflects both physiological and mental processes trying to adapt to a new situation [53]. This physiological response is not surprising as the neuro-cardiorespiratory system is known to be a nonlinear dynamical closed loop system which can oscillate at different frequencies [54]. The Eastern interpretation also shows that the psychological effect also follows this dynamic as indeed the three energies Tripa, Lung and Beken have both aspects of physical and mental.

The concepts of homeostasis and homeodynamic is well known from a physiological point of view, but rather poorly studied from a psychological perspective [14,37,55,56]. In the latter case, psychologist speak about the adaptation process which involves high level cognitive and emotional processes as well as natural environmental processes such as circadian rhythms and many other chrono-biological rhythms [57-59]. This adaptation process can be interpreted as the natural evolution of a system towards states of static or dynamic equilibrium such as a heated bath converges to a certain value of internal energy (called free energy) in equilibrium with its environment.[3,60,61] Our analysis of the heart-mind complex using the Eastern medicinal and energy balance concepts shows similar behaviour. Further investigations of the cross-road between ancient and modern traditions need to be performed to consolidate our results.

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