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Article

Thermal Signature Based Sleep Analysis Sensor

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Abstract: This paper address the development of a new technic in the sleep analysis domain. Sleep is defined as a periodic physiological state during which vigilance is suspended and reactivity to external stimulations diminished. We sleep on average between six and nine hours per night and our sleep is composed of four to six cycles of about 90-minutes each. Each of these cycles is composed of a succession of several stages of sleep, more or less deep. The analysis of sleep is usually done using a polysomnography. This examination consists of recording, among other things, electrical cerebral activity by electroencephalography (EEG), ocular movements by electrooculography (EOG) and chin muscle tone by electromyography (EMG). The recording is done mostly in a hospital, more specifically in a service for monitoring the pathologies related to sleep. The readings are then interpreted manually by an expert to generate a hypnogram, a curve showing the succession of sleep stages during the night in 30-second epochs. The proposed method is based on the follow-up of the thermal signature that makes it possible to classify the activity into three classes: "awakening", "calm sleep" and "agitated sleep". The contribution of this non-invasive method is part of the screening of sleep disorders, to be validated by a more complete analysis of the sleep. The measure provided by this new system, based on temperature monitoring (patient and ambient), aims to be integrated into the tele-medicine platform developed within the framework of the Smart-EEG project by the SYEL - SYstèmes ELectroniques team. Analysis of the data collected during the first surveys carried out with this method showed a correlation between thermal signature and activity during sleep. The advantage of this method lies in its simplicity and the possibility of carrying out measurements of activity during sleep and without direct contact with the patient at home or hospitals.

Keywords: thermopile sensor; actimetry; thermal camera; data classification; tele-medicine; polysomnography;

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1. Introduction

Sleep is a state of relative consciousness in which man and all living beings in general invite him voluntarily or involuntarily to a phase of physical and moral recovery. The quality of sleep affects our mental and physical well-being and can play a mediating role in interpreting our socioeconomic status [1]. In [2], the authors studied the sleep relationship with the immune response regulation process and concluded that sleep deprivation altered immune function and conversely, immune dysfunction will ultimately alter the quality of sleep. Sleep is thus frequently disturbed in the case of critically ill patients who often suffer from mediocre sleep and loss of circadian rhythm [3]. The author in [4], based on the work of [5], presents a review of the role of slow sleep and paradoxical sleep in the consolidation of the memorization process, a particular challenge for future research.

Understanding the structure of sleep began early enough based on observing and recording the experience of a night's sleep. Sleep occupies a good part of our life and intervenes in the physical and psychological recovery. The interest aroused allowed the appearance and the evolution of instruments of analysis of sleep such as the Electroencephalograph in 1937 which makes it possible to record the cerebral activity from the electrical signals recorded in different positions of the scalp.

The signal obtained is an electroencephalogram (EEG). Several aspects of the experience of a night of sleep have motivated several research themes related to the study of sleep. The management of respiratory or behavioral pathologies during sleep caused the authorities to create specialty poles in sleep medicine and they provided hospitals and clinics with sleep analysis centers. Medical centers specializing in the management of sleep-related pathologies have acquired a set of instruments in addition to the Electroencephalograph to record several physiological signals at the same time. In addition to electroencephalogram (EEG), an electrocardiogram (ECG) to monitor heart rate, an electromyogram (EMG) to monitor the electrical activity of the muscles (chin and leg) and an electrooculogram (EOG) for eyes. Sleep, long considered as a cessation of activity and a slowing of metabolism, suddenly changed in 1953 when paradoxical sleep was discovered, which introduces a period of intense cerebral activity [6]. The sleeping period is organized in five or six cycles of 90 minutes each, these same cycles consist of stages ranging from awakening to deep sleep and paradoxical sleep through light sleep. The authors of [7] provide an overview of the organization of normal human sleep and highlight the importance of a clear appreciation of the characteristics of sleep to provide a solid context and a model to understand the clinical conditions in which "normal" Are altered. The author of [8] presents investigations into the physiological processes involved in the synchronization and regulation of our daily cycles of sleep and wakefulness.

In [17], the problems of recording and analyzing biomedical signals as well as methods exploiting their various characteristics during sleep are discussed. The use of signals recorded during sleeping period results in a night's sleep experience in the form of a hypnogram, which consists of a succession of stages relating to different stages of sleep. The doctors and researchers have established criteria allowing them to somehow translate the signals obtained with a polysomnography examination into a hypnogram. These criteria forged the scoring techniques as early as 1937 with the EEG signals and subsequently evolved with the addition of EOG and EMG signals [16]. These criteria were recorded according to two methods: Rechtschaffen and Kales [9], considers the sleep staging in six stages and the second method have been proposed by the American Association of Sleep Medicine (AASM), [10] [11][15], since 2007 is the most popular method where the sleep staging is considered in five stages. Thus the author in [15], proposes a study of scoring methods based on a large number of markers, the objective is to examine areas of disagreement to inform future revisions of the AASM Manual for Sleep Logging and Associated Events .

To date, sleep scoring is always carried out based on a visual analysis of the recordings made. This method of obtaining a hypnogram is the reference in the analysis of sleep [6] even if new computer techniques try to produce hypnograms in automatic or semi-automatic ways [12] [14]. The author in [13] investigates the different methods of sleep classifications based on the visual analysis of chronograms recorded with polysomnography. The author in [13] thus compares these classical methods with new automatic methods. Concerning these methods based on visual analysis, the author [13] highlights the limitations due to the physiology of the human eye and the visual cortex. The advantage of automating scoring is the idea of saving time on the one hand and on the other hand proposing a procedure of scoring stable from one patient to another by adopting an algorithm whose quality is mastered of the scoring which can also constitute a reference for manual scoring.

The increase in the aging population, coupled with the complexity of examinations such as sleep analysis, has led to the emergence of research axes to defer some of this analysis and follow-up to patients' homes. The principle is to sort upstream before undertaking more in-depth analyzes, which would be carried out exclusively at the level of hospitals and retirement homes. In this approach, mobile polysomnography devices have been developed and are being used. However, the large number of wires (30) needed for this exploration influenced the acceptability of this technique. In addition, a doubt remains in the results and commits the doctors to propose to the patients to spend several nights in order to reach the appropriate conditions.

Among the simplifying ideas, most methods seek the link of sleep with physical activity or movement [20], body temperature or electro-dermic activity [21]. Among these methods, those based on the monitoring of physical activity have benefited from the rapid evolution of mobile applications. The latter are in most cases equipped with sensors such as accelerometers, which can be exploited to quantify the sporting activity or to follow the movement and the efforts in the games.

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These applications have served as a springboard for new health-related applications. Thus, applications have been developed that offer hypnograms-like graphs to provide information about the night's experience and even provide an assessment of sleep quality based on the proportion of deep sleep (less agitation) in night sleep. Other devices are offered in the form of wristbands and, according to the same principle, offer graphs and a sleep assessment. These devices require permanent contact with the patient. The authors in [18] review a set of research articles related to the use of actigraphy to analyze sleep. The author concludes that in the clinical context, actigraphy is reliable for assessing sleep in patients with insomnia and in people less likely to tolerate PSG. In [19], the authors exploit a video capture in the infrared domain to raise the level of activities of the wrist and the body and compare the results obtained with those of an activity measuring device based on a motion sensor.

In this paper, we describe a method that follows the same approach as that used in [22] the analysis of sleep in the sense of physical activity, analyzing the evolution of human thermal radiation overnight sleep. This thermal radiation is due to the internal heat of the human body whose fixed temperature is fixed around 37.2 ° C. Its variation outside the body is produced by the influence of the ambient heat. To capture this thermal radiation, in our method we used a thermopile sensor targeting the upper area of the human body (trunk and head). To label the experience of a night of sleep we included in the experimental device a thermal camera giving images in medical format and giving on the other hand information on the temperature of the target according to a spatial distribution. We also included a three-axis accelerometer to detect night movements. The synchronization of the data is achieved by measuring the acquisition time to the nearest second. Staging results with classification algorithms such as K-means or Gaussians Mixture Models (GMM) applied to the data of a labeled night's sleep confirm our approach to the use of heat radiation to perform a sleep analysis preparatory to a more in-depth analysis with methods using polysomnography. The measurement provided by this new system can be validated with the classical polysomnography-based method by integrating the sensor and its processing unit into the measurement chain realized by the telemedicine platform developed within the framework of the Smart-EEG project [23].

The rest of the document is organized as follows. Section 2 gives a brief description of the proposed device for analyzing sleep and the methodology used to exploit the data collected. The experimental results of this work are described in Section 3. In section 4, orientations for future work are identified and performance compared to conventional methods are discussed. Final remarks and future directions for current research are also given in this section 4.

2. Materials and Methods

2.1. Materials

The acquisition device used for sleep analysis process is shown in Figure 1. This system consists of a set of sensors positioned remotely from the patient and other sensors carried by the patient. Remote sensors are the thermal camera and the thermopile sensor. The sensors carried by the patient are the inertial unit and the local temperature sensors placed on the wrist, trunk and foot. Another local temperature sensor is used to measure the ambient temperature. In adding the inertial unit, we improve the results of some wearable devices, which the results is based on the monitoring activity by the tri-axial accelerometer sensors.

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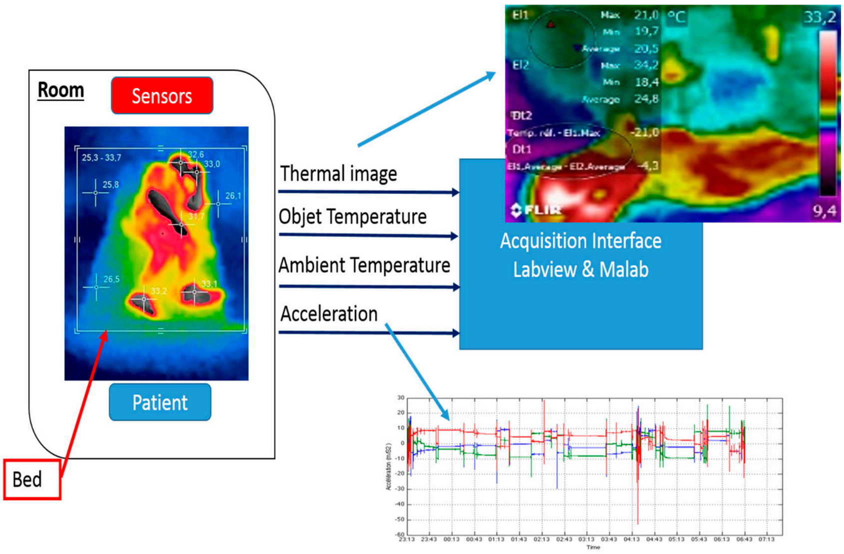
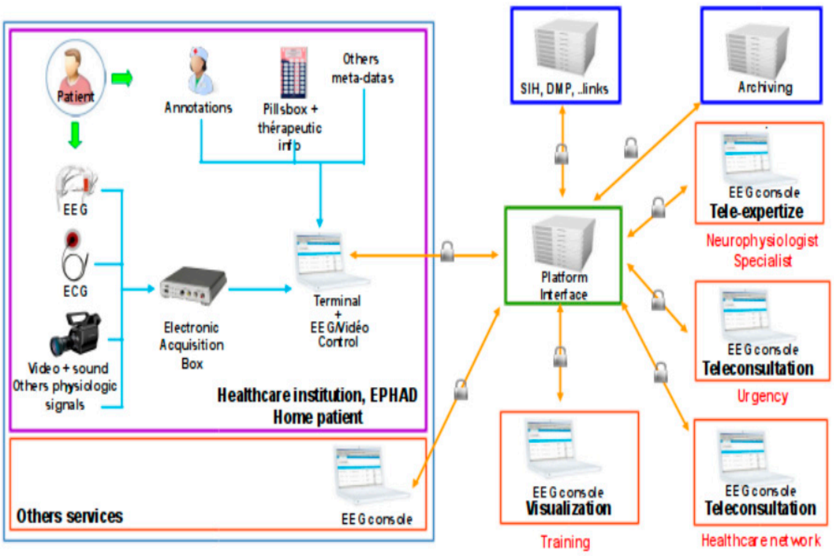


(a)



(b)

Figure 1. a) Experimental setup for data collection overnight sleep. b) The measure provided by our new system (a), based on temperature monitoring (patient and ambient), aims to be integrated into the tele-medicine platform (b) developed in the framework of the Smart EEG project by the SYEL team of LIP6 [23].

2.1.1. Sensors and measured quantities

The architecture of the final sleep analysis device is built around the thermopile sensor. We chose a sensor with a wide field of view to gain sensitivity. The TMP007 is a thermal infrared (IR) sensor sensitive to radiation in the IR spectrum from approximately 4- to 16-μm wavelength. The TMP007 measures the temperature of an object by sensing the infrared radiation emitted by the object and converting the voltage generated to a digital reading of the temperature.

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Table 1. Description of the sensors.

	Thermopile	Thermal Camera	Accelerometer	iButton
Frequency sampling (Hz)	1	0,1	100	< = 0,016
Reference	TMP007	FLIRC2	XSENS	DS1921H/Z
The measured data	Room temperature and patient and bed set	Thermal images and temperatures of the targeted area	Acceleration according to 3 axes	Skin temperature
Sensors				

2.1.2. Data Collection protocol

2.1.2.1 Thermal Image Sequence by Thermal Camera

Thermal images are acquired every 10 seconds. These images in medical format allowed us to obtain two pieces of information each time. The main information is the experience of a night of sleep obtained by visual analysis by the expert in order to label the different events related to the patient's posture changes in the bed. The second information extracted from the thermal images is the evolution of the temperature corresponding to two zones: the first targeting the upper part of the "bed + patient". The second zone is chosen to target a region whose temperature is close to ambient temperature.

2.1.2.2 Upper "Bed+Patient" Temperature by Thermopile Sensor

The final objective of our project is to develop a sleep analysis device based on the use of a thermal sensor composed of one or more thermopile sensors. Our choice was made on the TMP007 [30], a thermopile sensor built around a network of micro-thermocouples embedding an electronic circuit. The sensor outputs at a rate of one measurement per second a potential difference proportional to the radiation sensed. A calculation from this quantity resulting from the radiation emitted by the targeted zone and the ambient temperature allows us to obtain the temperature corresponding to the targeted zone. The sensor measures the ambient temperature on its own from a conventional temperature sensor placed judicially in the circuit so as to be thermally insulated therefrom. The accuracy and errors of remote temperature measurements by thermal sensors are largely related to the quality of the ambient temperature measurement.

2.1.2.3 Acquiring Wrist Acceleration.

In order to compare the responses of the thermopile sensor with the responses of the most popular systems in the analysis of sleep by wristwatch instruments with accelerometers and carried on the wrists, we have inserted in our device an inertial unit of XSENS [26]. The acquisition is carried out at a frequency of 100 Hz. The measurement makes it possible to obtain the acceleration of the wrist according to the three axes. This choice of using an inertial unit is linked to the possibility of supplementing our estimation of the motion by the angular velocity vector of the wrist along the three axes.

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2.1.2.4 Wrist, Distal and Proxima Skin Temperature by IButtons

Several works [29][27] refer to the links between body temperature and sleep. We distinguish between two types of temperature-related data, which tell us about the body temperature, which must be stable around 37.2 ° C, and those related to the cutaneous or skin temperature, which varies according to the ambient temperature and also the measurement location. The link with sleep is exploited in the study of sleep by analyzing the circadian rhythm. This rhythm is accompanied by a rather fine variation of the body temperature less than one degree Celsus around 37.2 ° C. The alternation day / night corresponds, on the one hand, to the awakening / sleep alternation and to the alternation between high temperature and low temperature.

During sleep, the body temperature decreases while it increases during the day. The cutaneous temperature, unlike the body temperature, increases during sleep and decreases during waking. Work in [28], relate the unifomization of the cutaneous temperature of all the body during the deep sleep. To complement our knowledge we have a set of temperature sensors of type IButtons [29] that have the appearance of buttons of jackets that operate autonomously. The measurements are taken at a rate corresponding to one measurement per minute. A sensor of the same type will give an estimate of the ambient temperature.

2.2. Methods

2.2.1 Data Features Extraction and Filtrage

The data are collected at different frequencies, but the time axis is set by universal time, which facilitates the first comparison of the various data in order to look for correspondences between these heterogeneous quantities.

The reference in terms of classification of the sleep is the classification obtained in the case of the analysis of the sleep by a polysomnography. In this process, the total duration of the recording of the data is subdivided into epochs of 30 seconds each and sometimes less in the case of certain pathologies (sleep apnea). The manual approach based on observation of recorded signals consists in the assignment of epochs to the different stages of sleep.

To exploit the data in order to test the classification, we decided to resample the data series according to two acquisition rates:

- 1 Hz, to operate at the same frequency as the thermopile sensor.
- 0.1 Hz, to operate at the same frequency as the thermal imaging camera.

As proposed by several authors initiating and using accelerometer-based actigraphs, before rearranging the raw data, we have filtered the accelerometer data through a band-pass filter in the range of .3 to 3 Hz, an interval corresponds more of voluntary movements.

2.2.2. Data clustering and classification using the K-means algorithm

Our first approach to data analysis is to see if there is a natural tendency for data to reflect the indications obtained by the process of labeling. For this, we used a so-called K-means algorithm [25] whose principle is to group data according to a Euclidean distance criterion.

3. Results

The experiment carried out consisted in the recording overnight of the following data: ambient temperature, bed and patient temperature in two ways thermopile and thermal camera, acceleration of the movement of the right wrist see table 2.

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3.1. The collected data

Table 2. Description of the collected data.

Data	Thermopile	Thermal Camera	Accelerometer
Frequency sampling (Hz)	1	0,1	100
Quality of FS(%)	100	97,65	94,96
Number of Observations	28591	2865	2703130
Collection time	23:12:59 to 07:09:29	23:10:26 to 07:08:42	23:12:59 to 07:09:29

3.1.1 Thermal Temperature

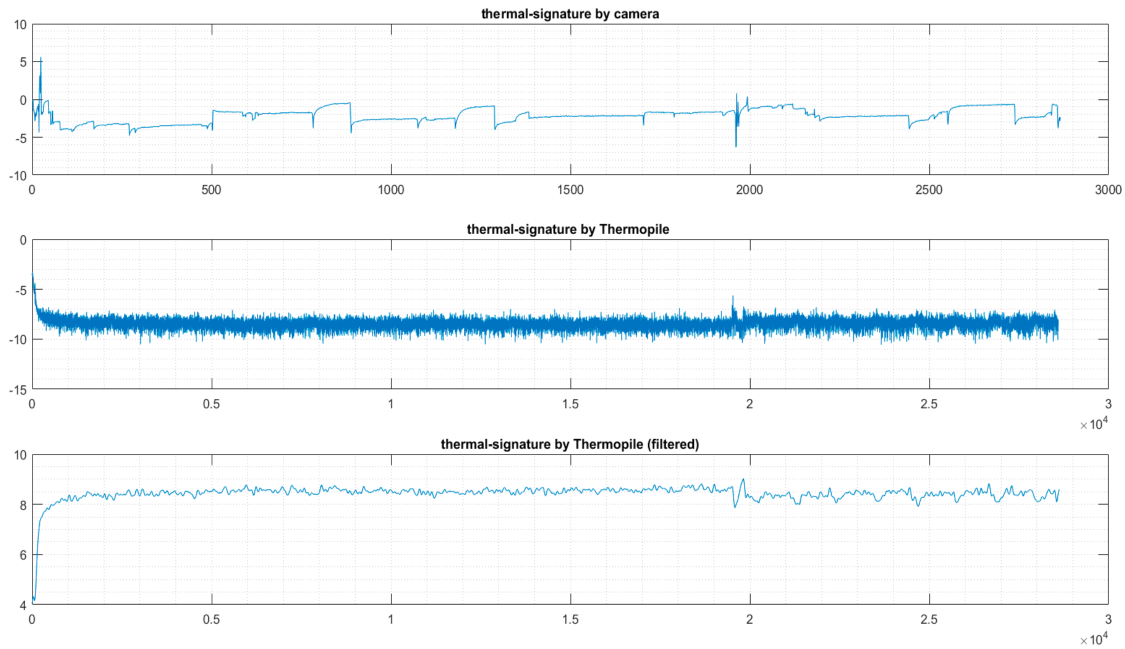

Figure 2. This figure shows the thermal signature obtained with the measurements made with the thermal camera and with the thermopile sensor filtered and unfiltered signal.

The thermopile sensor having a larger field of view around 90 ° is placed above the bed at a distance close to 2 meters. We initially chose this configuration to ensure that we capture all the radiation emitted by the patient and bed set. The signal obtained is rather noisy; the filtering does not adjust the signal that does not correspond to the signal obtained with the camera.

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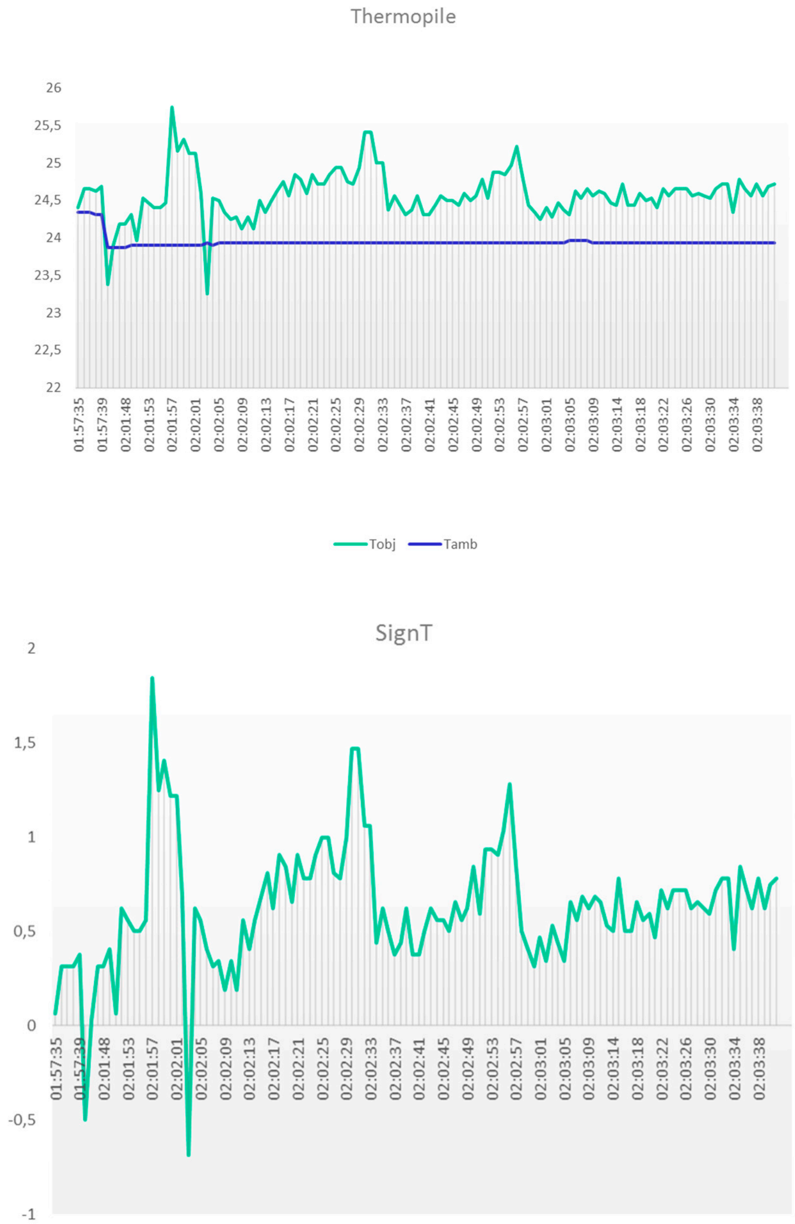

Figure 3. Response of the thermopile sensor after modification of the measurement conditions.

We have improved the signal of the thermopile, which has become less noisy and more exploitable as shown in Figure 3. This improvement in measurement is obtained when, on the one hand, the sensor is away from the electronic circuit composed largely of the circuit intended for the various calculations and on the other hand, when the thermopile sensor, for example by using a diaphragm, reduces the target zone. The distance of the sensor from the treatment circuit allows us to measure an ambient temperature closer to that of the patient's room.

3.1.2 Skin Temperature

In Figure 4, it is observed that the axillary temperature under the armpit is more stable and elevated compared to those of the hand or the foot. During sleep, the body temperature decreases while it increases during the day. The cutaneous temperature, unlike the body temperature, increases during sleep and decreases during waking. In Figure 5 is presented the distal-proximal gradient (DPG) corresponding to two days and one night of sleep. The goal is to explore the possibilities to predict sleep-onset latency of night-time sleep for infants as mentioned in [24].

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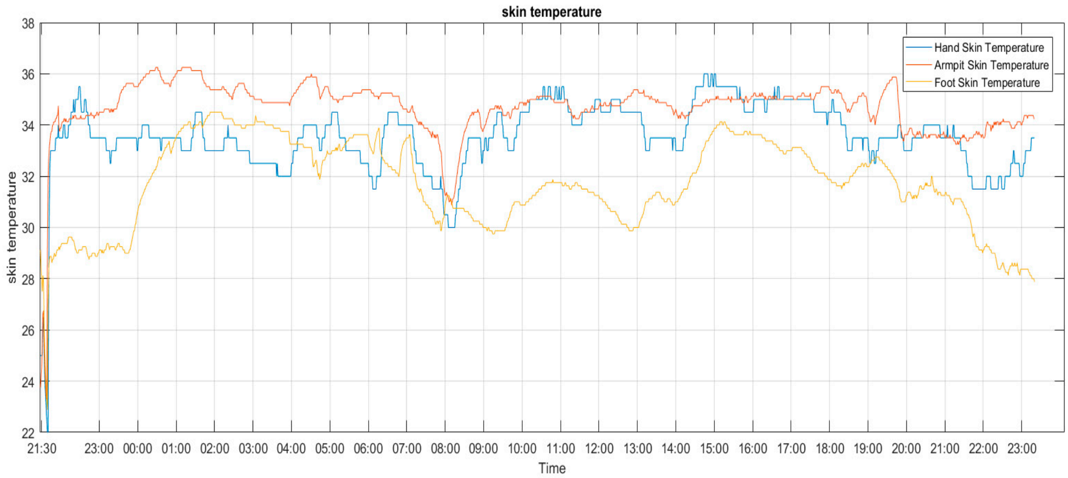

Figure 4. Wrist, Distal and Proxima Skin Temperature measurement by IButtons

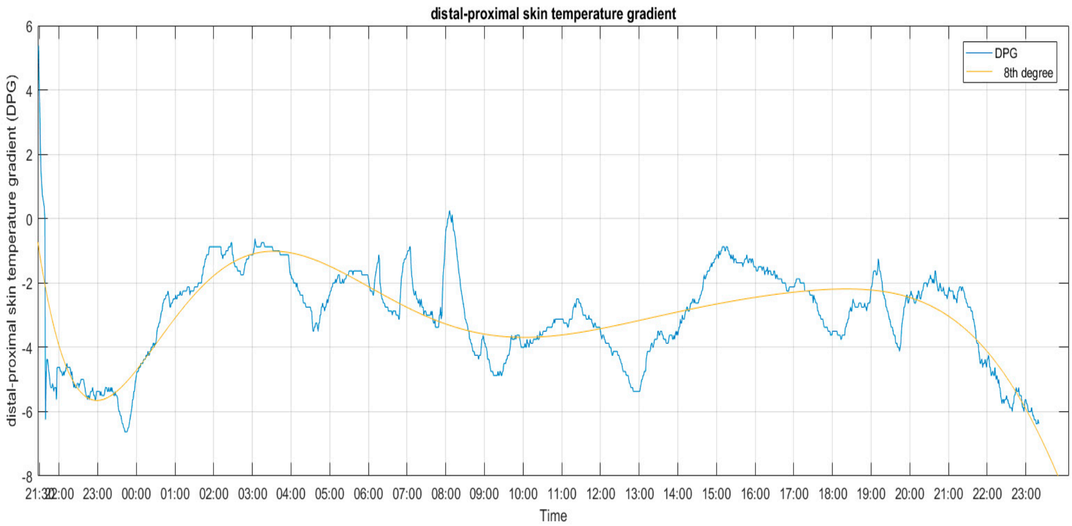

Figure 5. Distal-Proximal skin temperature Gradient (DPG) of two day and one night

The authors in [27] study the link between Sleep and Body Temperature and use the DPG to make a link with the circadian rhythm and the sleep cycle.

3.1.3 Acceleration Module

The movement of the patient during the night informs us about the character of sleep in terms of peaceful or restless. One of the most used sensors to follow the movement is the inertial sensor. The figure 6 below shows the raw measurements of the acceleration of the right wrist movement along the three axes.

On top of another graph representing the acceleration module which indicates the occurrence of movements during the night.

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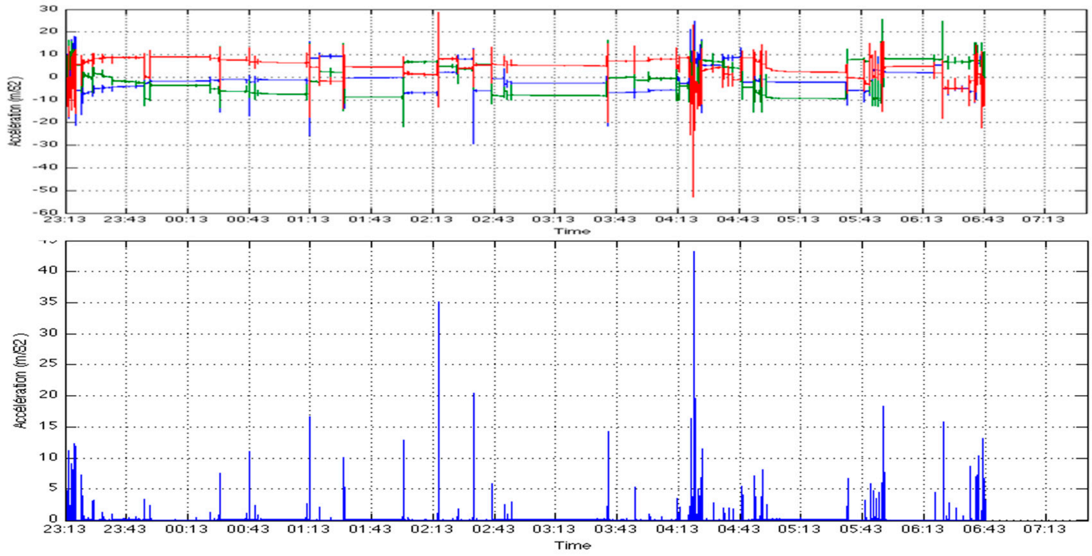

Figure 6. Acceleration of the movement of the right wrist along the three axes.

3.2. Comparison of thermal radiation and actigraphy

The results obtained validate as shown in Figure 7, the use of the thermal radiation in place of the actigraphy data proposed by the portable apparatuses.

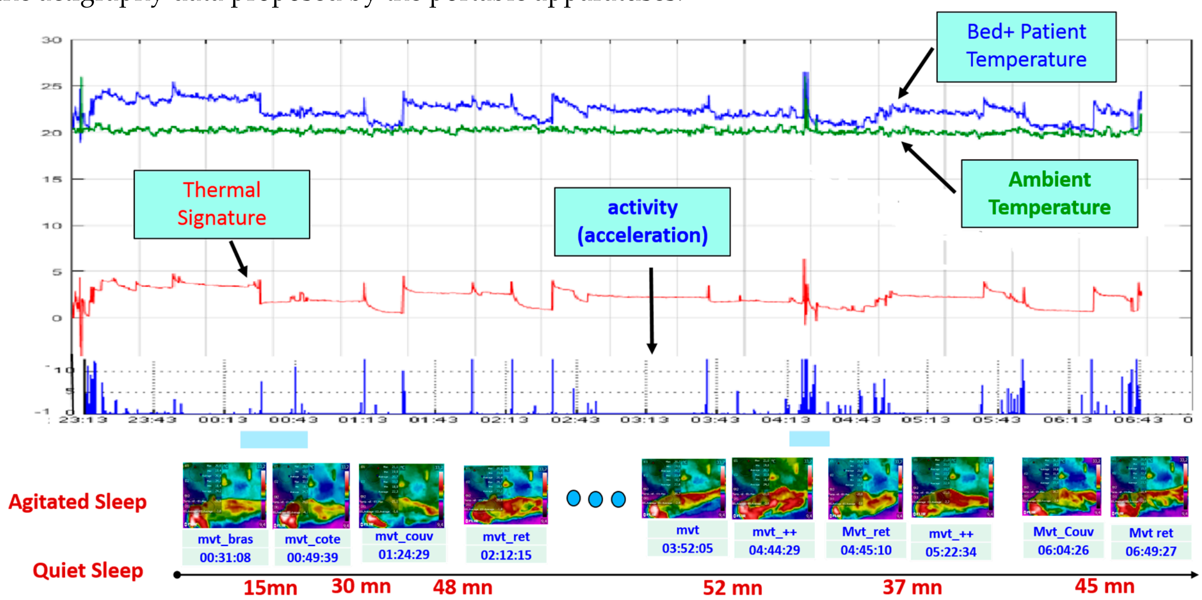

Figure 7. This figure shows the evolution of the ambient temperature, the temperature of the bed and patient and the activity represented by the acceleration of the movement of the wrist. The thumbnail images represent the instants associated with movements, and then the durations corresponding to rest periods without activity are displayed.

3.3. K means Classification of data collected overnight

For this, we have applied a K Means algorithm inspired by the method proposed in [25]. The result is presented in graphical form in Figure 8. It is noted that stage 1 occupies the beginning of sleep and then when the patient leaves the bed, this observation indicates that stage 1 corresponds to a state of awakening. Stage 5, which is very present in the early stages of sleep, returns during the night to a fairly low degree. It is more akin to periods of passage between two stages: from light sleep to deep sleep or the opposite. The other stages 3 and 4 correspond more to a phase of light sleep whereas stage 2 is more a tendency to deep sleep.

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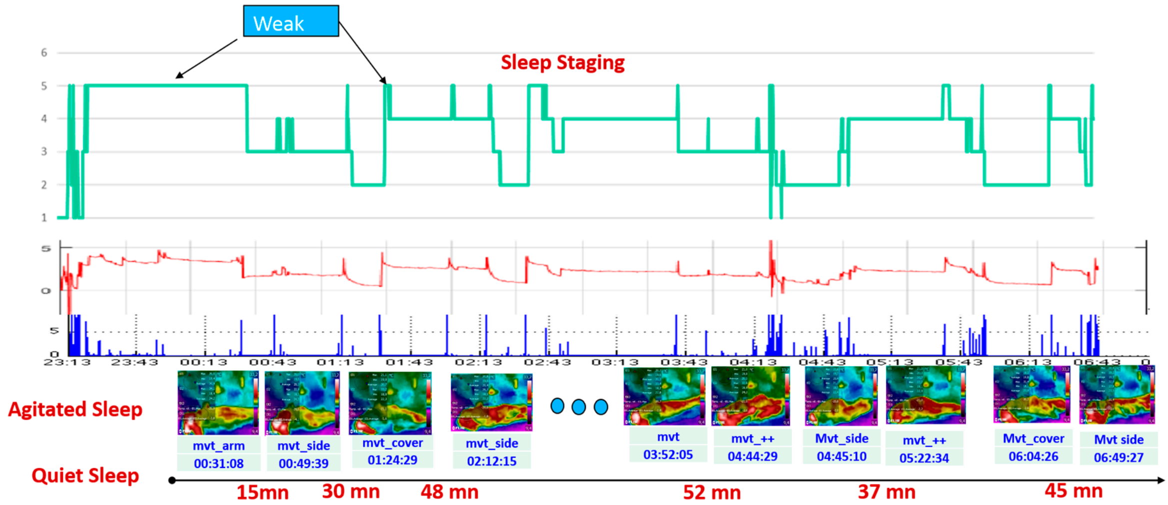

Figure 8. This figure shows an example of classification of the sleep from the data of the thermal signature. The algorithm used is K-means by choosing five clusters.

4. Discussion and Conclusions

In this paper, we proposed a non-invasive method of sleep analysis based on measurement of thermal radiation. The use of the data obtained both in comparison with the others and in classification have made it possible to evaluate the contribution of the various sensors. One of the important results is the confirmation of the advantage of using a thermopile sensor oriented on the upper part of the body. This result confirms and improves the predicted result in [22]. Another result is obtained with the use of the thermal camera, first the camera allowed us to explore the solution in the case of using several sensors to spatially discretize the measurement. Then, the thermal camera combined with a specialized software enabled us to obtain images in medical format that allowed us to label the recorded data. In addition, we validated the various events related to the actimetry occurring throughout the night from the accelerations of the direct and indirect movement of the patient's wrist using an inertial unit carried at the level of a patient's wrist. The results reinforce us to continue this work to collect more data and with more patients. This work in perspective necessitates in advance implementing the computer tools in an embedded system in order to facilitate the use in the context of use in telemedicine in the framework of the Smart-EEG project. This final solution will also bring another reference in the classification that obtained with a polysomnography for the analysis of sleep.

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Supplementary Materials: Upon request, it is possible to use the video, which takes up the experience of a night's sleep and the data of the different sensors: thermopile, IButtons and accelerometer. Send an email to sbaa91@gmail.com.

Author Contributions: A.S designed the experiments and wrote the paper. D.I has supervised this work and paper. The other authors of the paper contributed to the development of the methodology and analysis of the data.

Conflicts of Interest: The authors declare no conflict of interest.

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