

# Monitoring Nocturnal Heart Rate with Bed Sensor

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## Keywords

Nocturnal heart rate, signal quality, BCG, bed sensor

## Summary

**Introduction:** This article is part of the Focus Theme of *Methods of Information in Medicine* on “Biosignal Interpretation: Advanced Methods for Studying Cardiovascular and Respiratory Systems”.

**Objectives:** The aim of this study is to assess the reliability of the estimated Nocturnal Heart Rate (HR), recorded through a bed sensor, compared with the one obtained from standard electrocardiography (ECG).

**Methods:** Twenty-eight sleep deprived patients were recorded for one night each through matrix of piezoelectric sensors, integrated into the mattress, through polysomnography (PSG) simultaneously. The two recording methods have been compared in terms of signal quality and differences in heart beat detection.

**Results:** On average, coverage of 92.7% of the total sleep time was obtained for the bed sensor, testifying the good quality of the recordings. The average beat-to-beat error of the inter-beat intervals was 1.06%. These results suggest a good overall signal quality, however, considering fast heart rates (HR > 100 bpm), performances were worse: in fact, the sensitivity in the heart beat detection was 28.4% while the false positive rate was 3.8% which means that a large amount of fast beats were not detected.

**Conclusions:** The accuracy of the measurements made using the bed sensor has less than 10% of failure rate especially in periods with HR lower than 70 bpm. For fast heart beats the uncertainty increases. This can be explained by the change in morphology of the bed sensor signal in correspondence of a higher HR.

during sleep. Ballistocardiographic (BCG) signal can be measured with pressure sensors integrated into the bed mattress [3]. Several different measuring principles exist for pressure sensitive foils, like force sensing resistors (FSR), capacitive foils, piezoelectric polymer foil PVDF and electret foil Emfit [4]. Even though BCG can provide a reliable estimation of the HR signals for most of the time [5], there are challenges in measurement in presence of movements. In addition, while ECG is a measure of the electrical activity of the heart, BCG is related to mechanical variables related to the cardiac activity. For that reason attention should be paid when processing procedures are extended from (ECG-RRI) to BCG heart beat interval (HBI) series. In fact, variation in the heart rate (e.g. during tachyarrhythmia or ectopic beats) may generate a variation in the BCG morphology, with consequent misdetection of the cardiac beat [6]. In the present paper we are evaluating the reliability of HBI measurements for sleep deprived patients in presence of arrhythmias and altered heart rate with specific focus on tachyarrhythmia episodes.

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## 2. Methods

A bed sensor with multichannel BCG signal measurement has been developed by VTT. Three different physiological signals: heart beat interval, respiration and movement activity, are calculated on-board with embedded algorithms from the raw signals [7]. The bed sensor measurements were acquired in the Sleep Center of Tampere University Hospital with polysomnography (PSG) as a reference. Overnight PSG were recorded in 28 patients with suspected

## 1. Introduction

The quality of sleep is a topic that has attracted the interest of several researchers. In the last years, different solutions have been proposed for non-obtrusive recordings in non-clinical environment. A review of them is presented in [1]. In particular

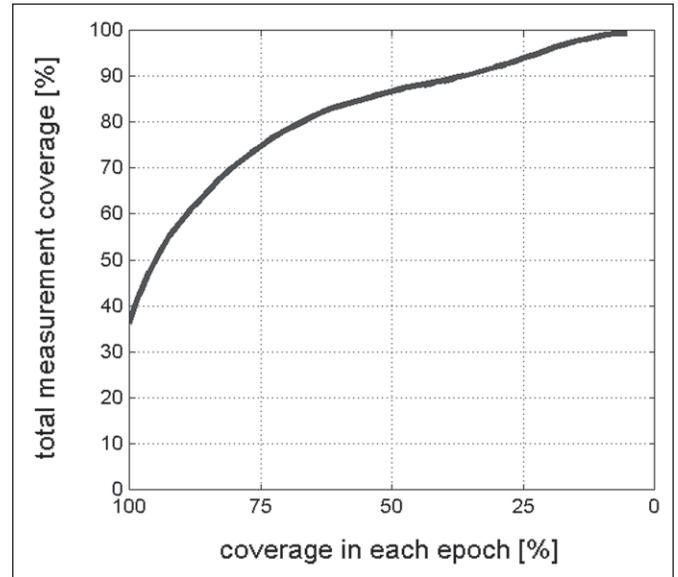
the nocturnal heart rate (HR) has been analyzed in several studies aiming to estimate sleep quality [2]. Heart rate is usually obtained from measurements of the electrocardiogram (ECG) by extracting RR interval series (ECG-RRI). Recently, non-contact sensors have been introduced in order to enable unobtrusive monitoring

sleep-disordered breathing (SDB). The age of subjects was between 49 and 68 years, the BMI varied between 21.8 and 40.6, 13 patients were females and 15 were males. The patients suffered from a variety of sleep problems, including either different degrees of nocturnal apnea/hypopnea and/or insomnia. Previously, the bed sensor had been tested on healthy young people, and this new test data with sleep deprived elderly patients gives a more realistic picture of its the clinical application. The increased level of movement activity during sleep causes strong artifacts in the heart beat signal detected from BCG. In addition, some of these elderly subjects had frequent cardiac arrhythmia episodes, and one patient was using a pacemaker, although none of them had acute cardiac problems during measurement. In this paper, the heart rate measurement obtained from the bed sensor is compared with the reference ECG-RRI. The analysis period for each patient was the total sleep time which was obtained from the PSG analysis report, and some time periods were removed where the ECG-RRI values were missing due to strong body movements or poor electrode contact. The HR was defined for epochs of 60 seconds for both measurements (ECG-RRI and bed sensor HR), and also the overnight HRs were compared. First, we summarize the measurement coverage and the error analysis for the bed sensor heart rate estimate with all 28 subjects and about nine-hour average recording time each. We noticed that especially the highest HR-values were difficult to measure with the bed sensor, and therefore six subjects having some periods with HR higher than 100 bpm are described with more details.

**2.1 Bed Sensor**

The bed sensor measures multiple BCG signals with eight channel pressure sensing PVDF foils, installed below the bed mattress. The heart beat extraction is based on the multichannel cepstra, using a sliding window Fourier-transform method explained in [8]. Spectrum for the heart beat signal is composed of the peaks at the harmonic frequencies of the fundamental heart beat frequency. This periodicity in the spec-

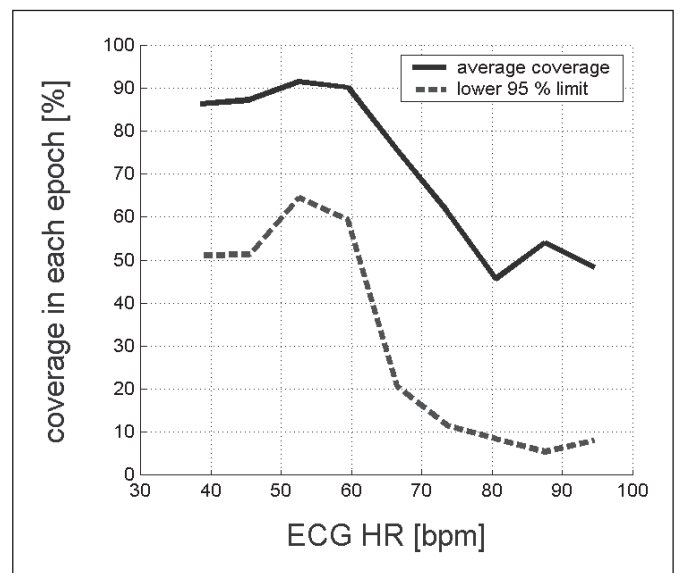
**Figure 1** Lower acceptance level for the epoch-wise coverage is in the horizontal axis and the total coverage is in the vertical axis. The cumulative distribution is for the whole test data.

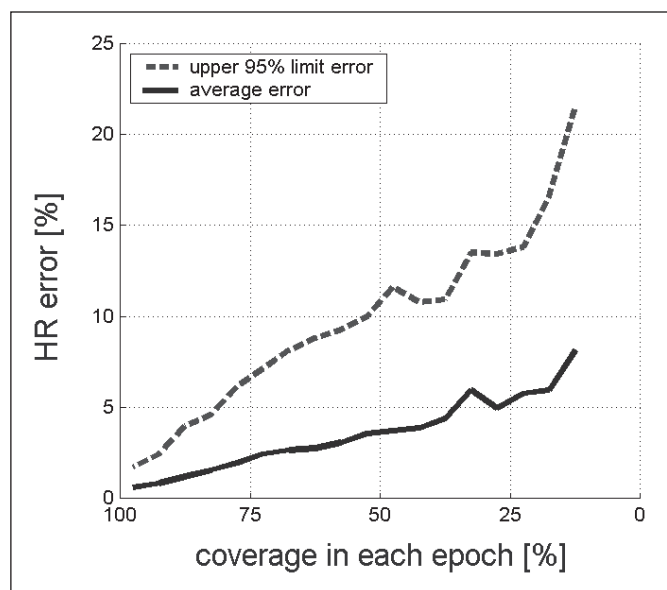


trum is shown as a peak value in the cepstrum located at the HBI time value. The heart beat signal quality is shown in the sharpness of the harmonic spectral peaks and in the strength of the corresponding cepstrum peak value. We have used this peak value by scaling it into a new variable “confidence” for each extracted heart beat interval. Examples of both harmonic spectral peaks and the cepstrum peak are shown in Figure 3 and Figure 4 of IEEE 2007 conference paper from Kortelainen and Virkкала [7]. The strength of the cepstrum peak is defined in the algorithm by firstly interpolating the cepstrum with spline interpo-

lation and then selecting the maximum peak value. We suggest that the interpolation regularizes the cepstrum peak shape and so forth we can select the maximum value to describe the peak strength. Interpolation of the cepstrum also improves significantly the location of the cepstrum peak at the lag time axis and so forth the measured heart beat interval value. Thereafter, experimental parameters are applied to scale and limit the confidence result into the percentage range between 0 and 100%, and during normal resting sleep position, it is more than 60%, while during movement artifacts it decreases below 30%.

**Figure 2** Horizontal axis shows the HR for the whole data set and the vertical axis shows the bed sensor coverage, with the averaged over all epochs (solid) and the lower 95% distribution limit (dashed).



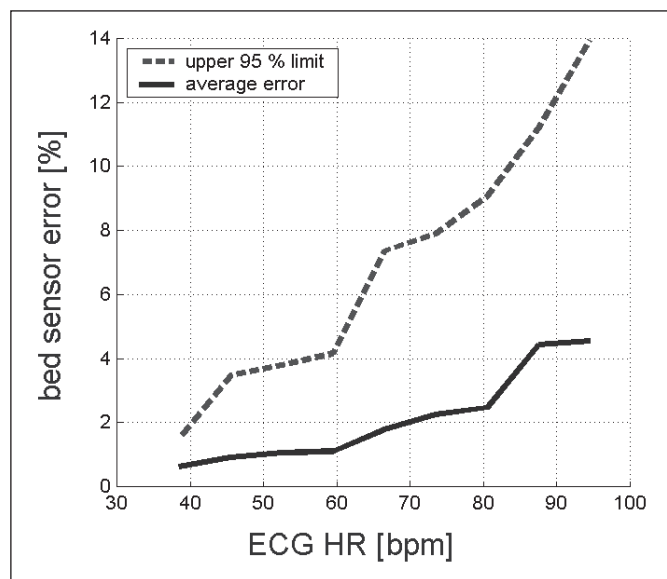


**Figure 3** Horizontal axis shows the lower acceptance level for the epoch-wise coverage and the upper axis shows the percentage error of HR estimate for each epoch.

## 2.2 Measurement Coverage

In order to obtain a reliable HR from the bed sensor, the periods with poor signal quality (which are associated with movements) have to be discarded. The sleep time percentage in which the signal is of good quality is here referred as “coverage”. The main artifacts for the heart beat extraction are movement activity and arrhythmia. We used a fixed threshold value of 30% for the confidence to limit our analysis on reliably detected heart beat values. The periods with movement artifacts have low confidence values and are

thus removed. The arrhythmia periods are detected and removed from the bed sensor HR results if the time duration between two consequent beats is more than 250 milliseconds. In principle, the ECG and BCG based HR should not be compared during arrhythmia periods, because the electrical and mechanical activities of the heart might not behave in a similar manner [6]. Both the HR and coverage were calculated for 60 second epochs. First, we looked for the optimum level of epoch-wise coverage to either accept or discard each epoch for the HR error analysis. ▶ Figure 1 shows that if we selected only epochs with at least



**Figure 4** Horizontal axis shows ECG HR and vertical axis shows the average bed sensor error (solid) and the upper 95% limit (dashed).

90% coverage, shown in the horizontal axis, it consists of only about a half of the total epochs and the total measurement coverage would decrease down to 50%. On the other hand, if we want to have total coverage of about 90%, we have to select epochs with as low as 25% coverage. Indeed, as the ▶ Figure 2 shows the epoch-wise coverage decreases with higher HR values. This is caused mainly by the fact that HR increases during movement periods. To have sufficient range up to 90bpm for HR measurement with bed sensor, we should accept epochs with coverage as low as only 10%. On the other hand, ▶ Figure 2 shows that for the normal range of HR between 50 and 70 bpm, the coverage is higher than 70%. ▶ Figure 3 shows the bed sensor epoch HR error distribution for different epoch coverages. As expected, the epochs with low coverage result in low reliability on HR. Finally, we applied a threshold of 25% coverage for the selection of epochs in the calculation of average HR. So forth, the percentage number of the selected epochs is 93%.

## 2.3. Heart Rate Measurement Uncertainty

By selecting only the epochs having better than 25% coverage, the average HR measurement error for the whole data set was 1% with total coverage of 93%. However, this accuracy level stands mainly on the normal range of HR only, which was also the main content of the data, while with higher heart rate values the uncertainty becomes worse. ▶ Figure 4 shows the bed sensor error distribution over individual epochs in function of the reference HR. The normal HR range up to 70 bpm can be measured with average accuracy better than 98%, but the error increases significantly with higher HR. For the HR above 100bpm, the epoch coverage was usually less than 25%, thus we decided to continue the analysis on that range based on individual heart beat interval values rather than as epoch averages.

## 2.4. Movement Pre-processing

To improve the detection of the fast HR values, we used the movement activity sig-

nal, measured with bed sensor as standard deviation of BCG signals with 4 seconds long sliding window. To remove effects of interpersonal variation, additional normalization was used on the movement signal, which consisted in a moving average on a 30-s window of the squared derivative of the movement. ▶ Figure 5 shows the movement signal before (top) and after (bottom) normalization.

### 2.5 Fast Rates Analysis Protocol

Different fixed thresholds were applied on the movement signal and on the confidence values in order to obtain the maximum HBI reliability. To do that, four parameters were extracted: coverage, sensitivity, false positive rate of beats with heart rate higher than 100 bpm (FPrate), and beat-by-beat percentage error (err). Sensitivity, FPrate and err are calculated starting from the confusion matrix. From the ECG RRI, True Positives (TP) and False Negatives (FN) are those beats which have or have not HBI correspondences into an interval that is equal to the refractory period estimated as:

$$\text{Refractory period} = 0.3 + \text{Average RR Value} \quad (1)$$

We chose this threshold in order to take into consideration that the BCG, a mechanical signal, may, in some circumstances, be considerably delayed with respect to the correspondent electrical signal.

False Positives (FP) are those HBI beats which don't have any correspondence in the ECG RRI signal, while True Negatives (TN) can't be calculated because in RR series there are not negatives. Thus sensitivity and FPrate are calculated using the following formulas:

$$\text{Sensitivity} = TP / (TP + FN) \quad (2)$$

$$\text{FP rate} = TP / \text{Total beats (with HR} > 100 \text{ bpm)} \quad (3)$$

Beat-by-beat error is the percentage difference between every HBI true beats and the corresponding ECG RRI beats. ▶ Figure 6 shows results of the four parameters with different thresholds on movement and

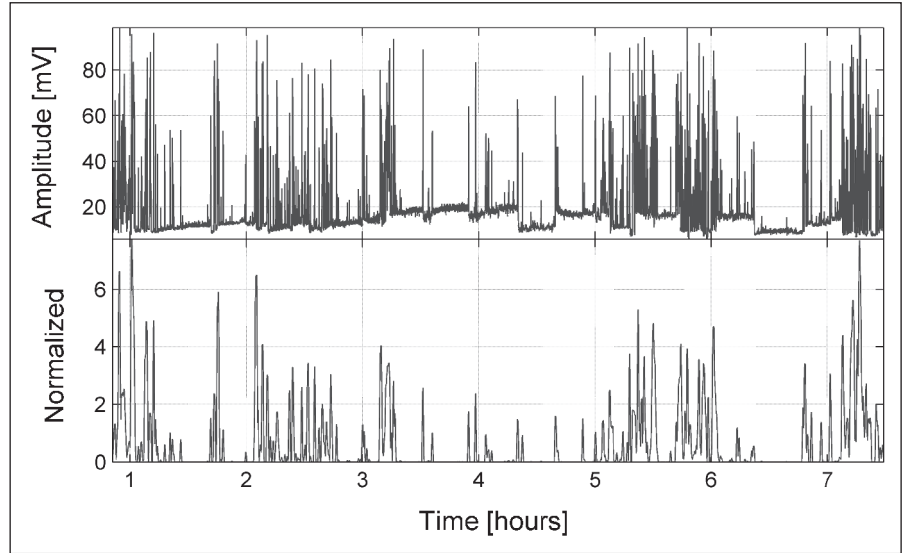


Figure 5 Movement signal before (top) and after (bottom) pre-processing

confidence index. In order to optimize the thresholds for every subject, a cost function was calculated:

$$\begin{aligned} \text{Performances}(i, j) = & A \times \text{sensitivity}(i, j) + \\ & B \times \text{coverage}(i, j) + C \times \text{err}(i, j) + \\ & D \times \text{FPrate}(i, j) \end{aligned} \quad (4)$$

where  $i$  and  $j$  represent threshold values for movement and confidence index respectively, while A, B, C and D are the costs of the four parameters and their values, expressed in ▶ Table 1, have been set to give more impact to high sensitivity, very low err and low FPrate (▶ Figure 7).

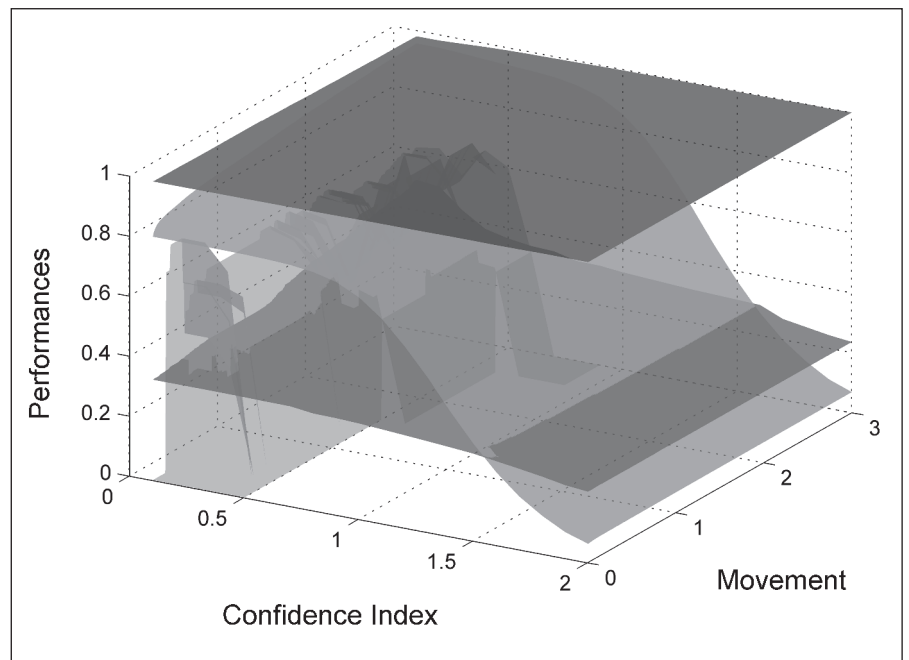


Figure 6 Performances of the four parameters with different thresholds on Confidence index and Movement. Sensitivity (dark grey), Coverage (grey) and FPrate (lighter grey) are expressed from 0 to 1, while Err (light grey) is expressed in percentage.

**Table 1** Costs for every parameter, the fourth column represents the cost value associated to every parameter included into the range defined by the second and the third columns.

	Low limit [%]	High limit [%]	Cost
A	0	70	0.33
	70	90	0.80
	90	100	1.00
B	0	50	0.20
	50	80	0.35
	80	100	0.50
C	0	1	0.00
	1	3	0.50
	3	5	0.80
	5	$\infty$	1.00
D	0	20	0.00
	20	45	0.50
	45	100	1.00

### 3. Results

The total average between all subjects gives 1.06% error with 92.7% coverage for the bed sensor HR measurement. Most of the subjects have coverage higher than 95% and less than 2% of error, but for three subjects, namely S06, S12 and S20, the bed sensor HR measurement coverage was less than 75%, due to continuous movement ar-

tifacts or strong arrhythmia. The analysis of fast rates (HR > 100 bpm), for the six subjects with tachycardia events, returned mid-high level performances. After optimizing movement and confidence index thresholds for each subject, the average sensitivity was 28.4% and the FPrate was 3.8%, for beats with HR above 100 bpm.

### 4. Conclusions

The accuracy of the average HR measurement with the bed sensor has less than 10% failure rate and this is in accordance with the guidelines reported in [9]; however, the system we are discussing in this paper is not for a standard clinical ECG, but is rather for a global evaluation of sleep quality in order to find anomalies during sleep and to perform a timely intervention. For the data periods with HR higher than 80bpm the uncertainty increases. In the case when the high HR is related to the movement activity during sleep, some sleep analysis could still be performed based on the respiration and movement signals. Bed sensor also tracks well immediately after the movement periods, and thus analysis of the decreased HR during relaxation is possible. Instead, the usefulness of the bed sensor for detecting tachycardia during sleep needs more consideration. In this study, a beat in HBI has a correspondence in ECR-

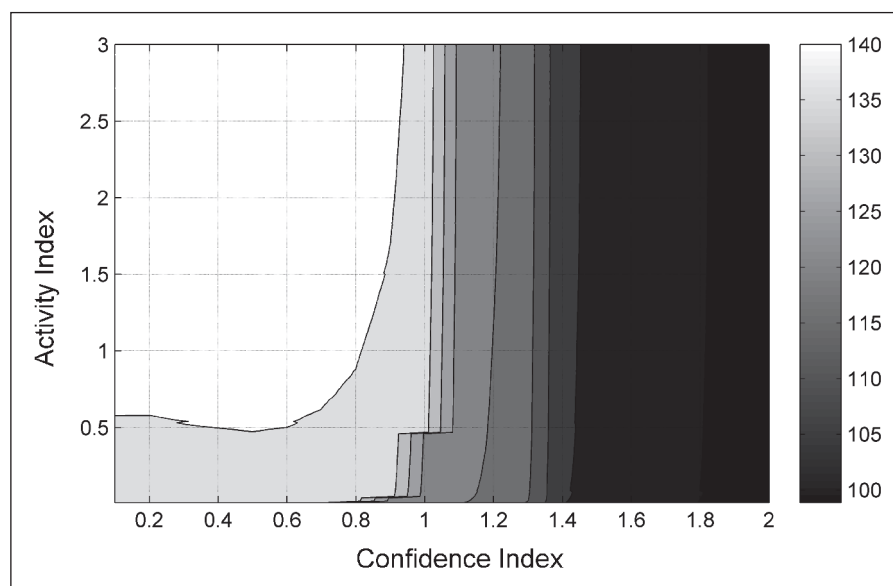
RRI if they differ for less than the 30% of the RRI value (about 330 ms). This threshold has been chosen in order to take into account the different nature of the two signals. In fact, the mechanical signal, mainly related to peripheral pressure, can be delayed with respect to the electrical ECG signal. To improve the sensitivity for high HR levels, we selected different threshold values individually for each subject both for the bed sensor heart beat confidence index and movement activity. The results show a very good reliability of detected beats but the sensitivity around 28% discloses that there are too many beats that cannot be detected. This will clearly influence the tachycardia detection. An explanation can be found in the variation in BCG morphology during accelerated heart rate. A better exploration of the BCG morphology should be required, taking into account the effects of the different sleeping positions. However, our data included only occasional and short periods of possible tachycardia, and further analysis is needed with data measured from subjects suffering from actual tachycardia. As a conclusion the clinician has to take into account these performances before using the bed sensor for clinical applications.

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**Figure 7** Cost function values for every Confidence index and Movement thresholds

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