

# A Selective EOG Removal Method for EEG Signals: The Multi-thresholding Technique



Quoc Tuong Minh , Sieu Le Thi Be , Khai Le Quoc,  
and Linh Huynh Quang

**Abstract** EOG is one of the major artifacts in EEG signal processing. There are varieties of methods have been proposed that aim to eliminate the influence of Ocular artifacts on the EEG signals. However, the problem is the trade-off between their performance of removing EOG artifact and their simplicity. In this study, we propose a simple and reliable method but giving a good performance. The idea of this method is to use a multi-threshold technique to target EOG contaminated parts in the signal then selectively subtract it out in order to get a corrected signal with a minimum alteration on the uncontaminated parts. In this study, we used triple-threshold, both in time and frequency domain, to target the contaminated parts (or EOG artifact component). The result shows that besides its simplicity, this method also reliable and effective when selectively removed some typical EOG artifacts like blinks or eye movements without altering other clean parts in the EEG signals. More than that, our method is also able to extract the estimated EOG artifact component from the EEG signal. The need for this method is only one single prefrontal EEG channel, no need for an EOG reference channel for the input. The source code of this method is freely available to download in the form of a MATLAB function by request. We encourage the researchers to give it a try.

**Keywords** Simple EOG artifact removal · Electroencephalogram (EEG) · Electrooculogram (EOG) · Multi-thresholding technique

## 1 Introduction

EOG artifact (or Ocular artifact) is very common and dramatically influences on EEG signal. Especially, eye blink and eye movement are two major sources of the ocular artifact that cause the most impact on the EEG signal, both in amplitude

---

Quoc Tuong Minh and Sieu Le Thi Be: These authors contributed equally.

---

Q. Tuong Minh (✉) · S. Le Thi Be · K. Le Quoc · L. Huynh Quang  
Department of Biomedical Engineering, HCMUT-VNU, 268 Ly Thuong Kiet Street, Ho Chi Minh City 70000, Viet Nam

and frequency perspective. Many researchers have proposed their methodologies to suppress the EOG artifact that all work so effectively. However, the problem of those methods is the trade-off between the performance of removing EOG artifact and their simplicity. For that reason, researchers in the BCI research community are spending their attention on finding a simple, fast, and reliable method to minimize the effect of those EOG noises without the need for the EOG reference channel instead [1]. For example, authors of [2] and have proposed a method that used only one prefrontal channel EEG.

There are many well-known algorithms to eliminate EOG artifact without EOG reference such as Wavelet + ICA hybrid [3], ICA – Independent Component Analysis [4], Regression + ICA hybrid [5], template matching based [6], Stationary Wavelet + Adaptive thresholding [7]. Those methods are all showed very good results in SNR increase, RMSE reduction, or increase in accuracy and sensitivity. However, they are such tough algorithms to understand and implement, especially with non-Computer-science-background students and researchers. Because of that reason, researchers and students with non-Computer-science-background are commonly using either coefficients threshold like wavelet coefficient in [8] or high-pass method like in [9] because of their simplicity and acceptable performance.

Since coefficient thresholding and high-pass filtering are simple and a little bit effective, we proposed a method that combines both of their main ideas to keep their simplicity while gaining a better performance. The combining is using thresholds in both the time and frequency domain. The uniqueness of our method is that we did not use a conventional coefficient like the wavelet coefficient. Instead, we have proposed using a cubed and scaled amplitude coefficient with multiple threshold values both in time and frequency domain. It helps target the contaminated parts in the signal and selectively subtracts it out to avoid altering other uncontaminated parts in the signal. We also compared our result with the wavelet coefficient thresholding method and high-pass filtering method when applying those on the semi-simulated signal taken from the EEG-EOG data set of Klados and Bamidis [10] to achieve a more objective evaluating. The result shows that our proposed method is simple and has better performance than the conventional thresholding and high-pass filtering method.

## 2 Materials and Methods

### 2.1 EEG-EOG Data Set

As mentioned in the introduction section, to obtain an objective evaluation for the outcomes, we have used the semi-simulated EEG-EOG data set of Klados and Bamidis [10]. They created the data set to help researchers evaluate their EOG artifact removal method performance objectively. They recorded the signal at 200 Hz

sampling frequency, Notch filtered it at 50 Hz, and band-pass filtered it at 0.5–40 Hz. The data set contains samples from 27 subjects (males and females) with 19 electrodes placed according to the 10–20 International system layout. Each sample lasts about 30 s. The data set contains 4 files: “Pure\_Data.mat” is EOG artifact-free EEG signal recorded during eye closed, “HEOG.mat” and “VEOG.mat” are respectively horizontal and vertical EOG data, and finally, “Contaminated\_Data” is the semi-simulated EOG artifact contaminated data created by the following formula:

$$\text{Contaminated\_EEG}_{ij} = \text{Pure\_EEG}_{ij} + a_j \text{VEOG} + b_j \text{HEOG} \quad (1)$$

where index  $i$  indicates the subject’s number and index  $j$  is for the electrode’s number. Finally,  $a_j$  and  $b_j$  are the contamination coefficients of VEOG and HEOG, respectively [10].

We also would like to thank the authors of [10] have allowed us to use their data set.

## 2.2 A Summary of Influence of EOG on EEG Signal

Ocular (or EOG) artifact reflects the eye activities’ influence on the EEG signal, mainly by the electrical field in anterior of the head be changed due to the polarity of the eye globes. It causes a big impact on the electrodes near the eyes and quickly decreases its impact degree in the anterior–posterior direction. Eyeblink and eye movement are 2 types of activities that affect the EEG signal greatest [11, 12].

A blink happens in a very short duration, about 0.1–0.5 s, or 2–10 Hz frequency. The amplitude of blink artifact varies from about 40  $\mu\text{V}$  in the central plane, 80  $\mu\text{V}$  in the frontal plane, and over 200  $\mu\text{V}$  in the frontopolar plane. The authors of [11] also pointed out that blink artifact is bearing beneath the <5 Hz frequency range of the signal.

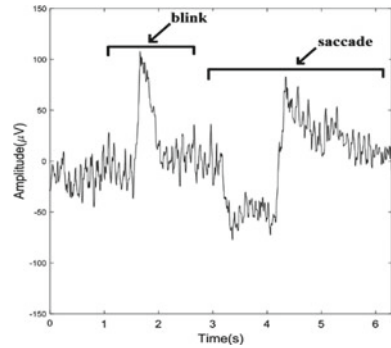
The rest type of EOG artifact is the eye movement or saccade, which can be seen both at horizontal and vertical EOG electrodes. The eye movement causes a longer duration, about 1.25 s (but just  $\sim$  150 ms for Onset-to-peak duration), and with approximately the same peak amplitude with eyeblink on EEG signals [11]. See Fig. 1 for an example of typical waveforms of blink and saccade artifact on the EEG signal.

## 2.3 The Methodology

The idea of our method has 2 main parts:

- Locating the contaminated parts in the signal, both in time and frequency domain.

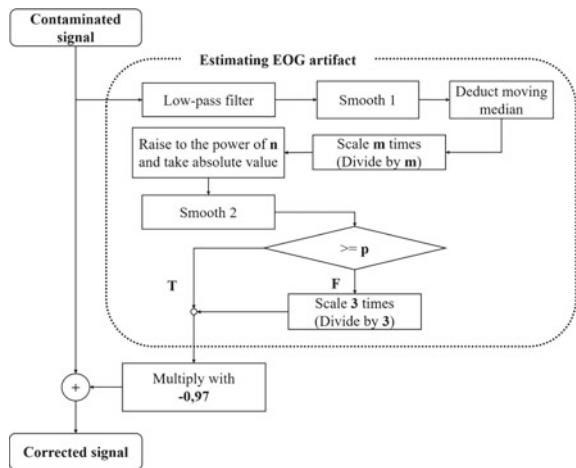
**Fig. 1** Typical waveforms of a blink and a saccade we extracted from Klados and Bamidis [10] data set



- Selective subtracting that component out to get a corrected signal with as least alter as possible on the uncontaminated parts.

The diagram in Fig. 2 explains the stream of the signal’s flow through steps in our

**Fig. 2** Signal processing flowchart



method.

**Detail explanation**

*(Note: In this study, we use the signal of referential montage to process. We have not tested on other montages yet.)*

- **Step 1:** Make out 2 copies of the original contaminated signal. One goes into the estimating process (denoted with a dotted frame), the other one is the reference signal for later subtracting step.
- **Step 2:** *Low-pass filter steps.* This step is primarily to extract the rough EOG artifact out of the EEG signal. We used **6 Hz** as a cut-off value because this value

is slightly higher than 5 Hz—the frequency that contains both blink and saccade artifacts, to be sure that all peak values are captured as correctly as possible.

- **Step 3:** *Smooth 1 step* helps attenuate the leakage frequency of the previous low-pass filter to gain better results in the final. Because the shortest duration of blink and saccade is about 100 ms long (or 10 Hz), we will take a bit shorter duration length  $0.08*Fs$  (or 12.5 Hz, slightly higher than 10 Hz) as the window width, where  $Fs$  is the sampling frequency, to retain peak values.
- **Step 4:** *Deduct moving median*. This step helps retain low-frequency characteristics of the signal in the contaminated part. To do this, subtract the resulting signal from step 3 with the value of itself after going through the moving median filter to exclude the low-frequency oscillations out of estimated EOG. A duration of 3–5 s is optimal for window width.
- **Step 5 and 6:** Steps 4 and 5 can be call *coefficient calculating step*. First, scale the signal  $m$  times to make the sample points lower than  $m$  become lower than 1. Then, we raised them to the power of  $n$  to make a distinct gap for scaled sample points gained above. The value  $m$  was set to 50 ( $\mu V$ ) as we found that this is the highest amplitude of below 5 Hz frequency oscillations in the awake adult's EEG signal. When choosing the value  $n$ , we individually tried with a different value and got  $n=3$  as optimal when applying to the data, using the ROC curve as the evaluating tool. **Remember to take the absolute value of the coefficient before going to the next step** to avoid a flat and discontinuous error for the best result.
- **Step 7:** *Smooth 2 step*. Step 4 and step 5 above makes the artifact's waveform narrower than its actual width. This step helps expand the width of them to make locating step to be more accurate. We advise using  $1*Fs$  to  $1.8*Fs$  window width because this is the average onset to end duration range of EOG artifact duration [11]. *Note: the bigger the window width, the more inclusive the artifact range we get accompany with more susceptible we cause to artifact-free trials. We empirically recommend value  $1.5*Fs$  as an optimal window width for natural eye open condition.*
- **Step 8 and 9:** *Comparing coefficient with threshold  $p$* . This step is to locate the contaminated trials (position and range). We have calculated the average maximum coefficient value for 50 clean trials (picked manually) and found that they are always below roughly 0.15. As a result, we have taken  $p = 0.15$  for the final threshold value. The value points below threshold  $p$  are considered as cleans and were scaled-down by 3 (30%) because these clean ones still include about 18–50% of EOG artifact in them (including type II error miss-detected trials) [11]. At the end of this step, we are now able to extract the estimated EOG artifact component in the contaminated EEG signal.
- **Step 10:** *Final step*. Scale the estimated EOG 97% and multiply it with  $(-1)$  to get a negative value. After that, plus the reference signal from **step 1** with the result. Due to the negative value, we can subtract (or in other word, eliminate) 97% of the estimated EOG when adding it with the reference signal. We use a 97% value because we do not want to strictly remove the estimated EOG since it is still just an estimated one, there are probably still have some components of

the EEG signal underlying in it. As 97% is just a semi-arbitrary value, in practice, researchers could use any value from 95 to 100%.

- For the rest of EEG channels on the head, use the result from step 8—the estimated EOG artifact, and remove it out from the desire channels, referencing their hemisphere. The only thing that changes between channels is the percentage value chosen to subtract artifact component out from the signal in step 8. Lins et al. [11] have described more detail about those percentages for different EEG channels.

This research applies the Declaration of Helsinki principles in human studies.

### 3 Result and Discussion

In this study, we compare the result of our proposed with 2 most relevant method: Wavelet Coefficient Thresholding (WCT) and High-pass Filtering (HF) in 2 perspective, quality and quantity.

#### 3.1 Quality Evaluating

The easiest way to evaluate the result of one EOG artifact removal method is by looking at how it altered our signal. A good filtering method will shift the EOG artifacts slipping down to the baseline and did as minimum as possible change on clean parts. Because we are using a semi-simulated data set, we have a pure signal as the reference for the corrected result.

For further comparison of the performance between the methods, besides the RMSE value, we also used an additional value  $\Delta SNR$  in percentage unit. The  $\Delta SNR$  was calculated using 3 simple steps. First, we calculated SNR of pure signal versus reference EOG signal and called it  $SNR_{ref}$ . Then, we calculated SNR for each of the used methods and called it  $SNR_{method}$ . Finally, the  $\Delta SNR$  was calculated using the following formula:

$$\Delta SNR(\%) = \frac{SNR_{method} - SNR_{ref}}{SNR_{ref}} \times 100\% \quad (2)$$

As seen in Figs. 3, 4, and 5, applied on over a hundred of contaminated trials from 54 samples of the data set, in average, the proposed method gives the best corrected-data, which is stick very close to the reference (average RMSE  $\approx 10$  for amplitude value, average RMSE  $\approx 2$  for PSD value) and do very little impact on clean trials (see Fig. 5). Also, Fig. 6 shows us the estimated EOG artifact component extracted by the method from channel FP1-ref is also very close with the real VEOG.

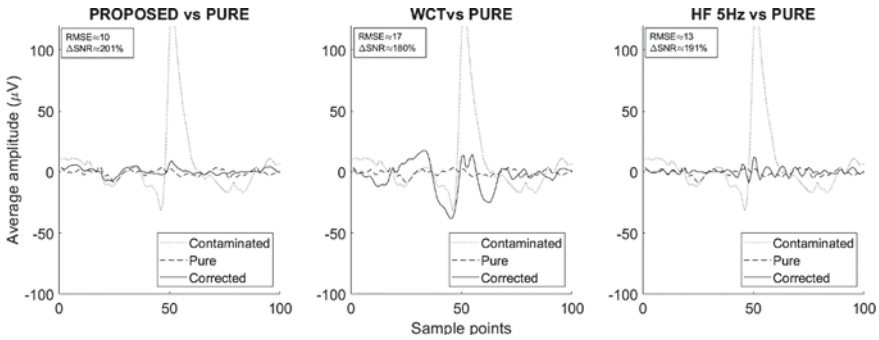


Fig. 3 Average amplitude before and after remove artifact of three methods

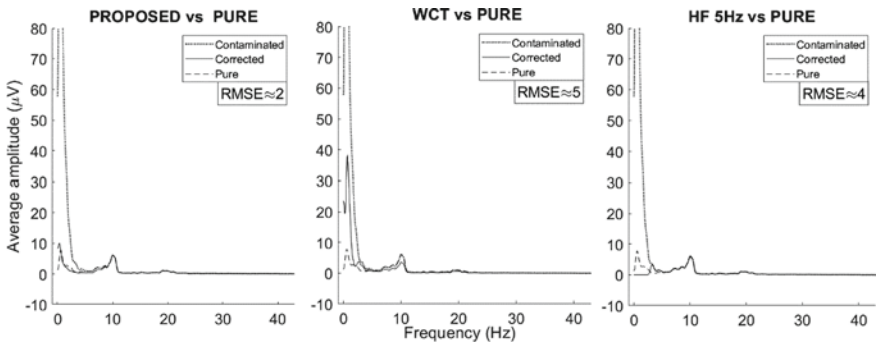


Fig. 4 The average value of PSD of before and after removing artifact result of three methods on contaminated trials

In short, our proposed method gives the most accurate corrected result compare with the reference pure signal in the visual look. It also gives a very accurate estimated EOG artifact component when compared with the real EOG signal.

### 3.2 Quantity Evaluating

Using T-test 2 sample with a significant level of 5%, we found out that the result of our method is better than the others in both time and frequency domain, but the same result in the effect of enhancing SNR value (see Fig. 7).

The proposed method gives RMSE value roughly 10 for amplitude and roughly 2 for PSD differences. It also helps double the signal-to-noise ratio (nearly 201%) (see Table 1).

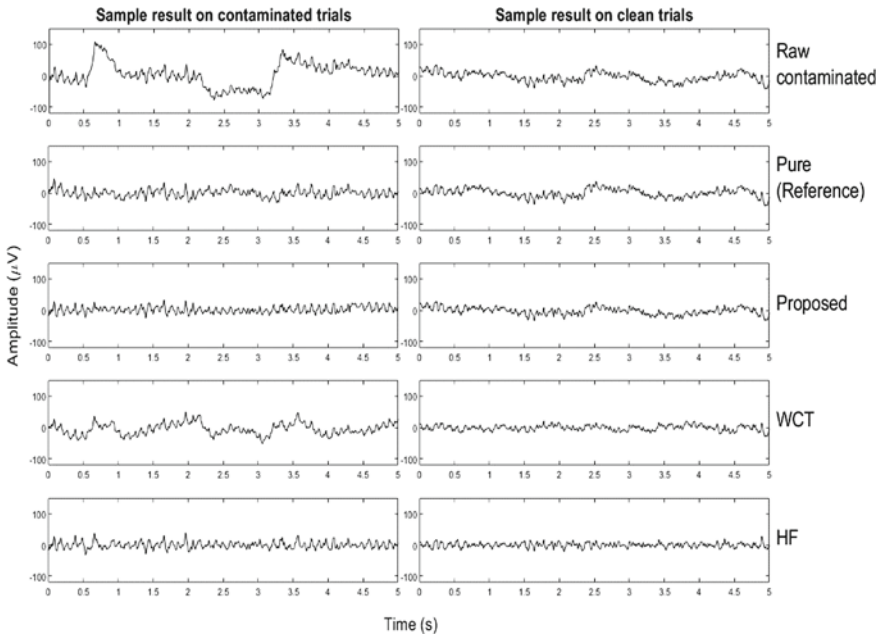


Fig. 5 One sample of result on contaminated and clean trials of the three methods

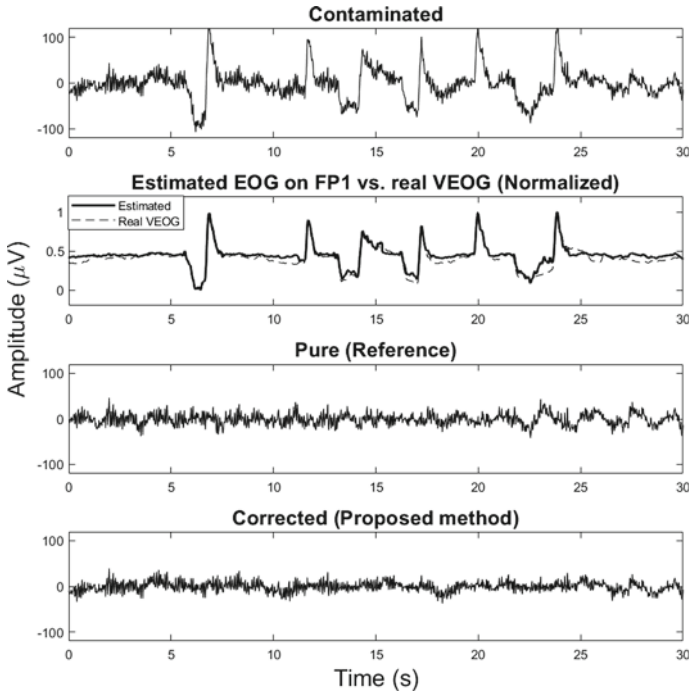
### 4 Conclusion

This study proposed a simple and effective method to remove the EOG artifact from the EEG signal, the Multi-Thresholding Technique. The first advantage of this method is that it was able to selectively remove the ocular artifact from contaminated trials without altering clean ones so much. Besides, only one frontopolar or frontal channel is required to detect contaminated trials. Also, FP1 or FP2 is the recommended channel, if possible, or F3 and F4 are the alternatives in the case FP channels are not available. Furthermore, this method was able to extract the estimated EOG artifact component from the contaminated signal. Furthermore, the proposed method also has better performance than the coefficient thresholding and high-pass filtering method. Last but not least, this method is very easy to implement with just a few simple steps.

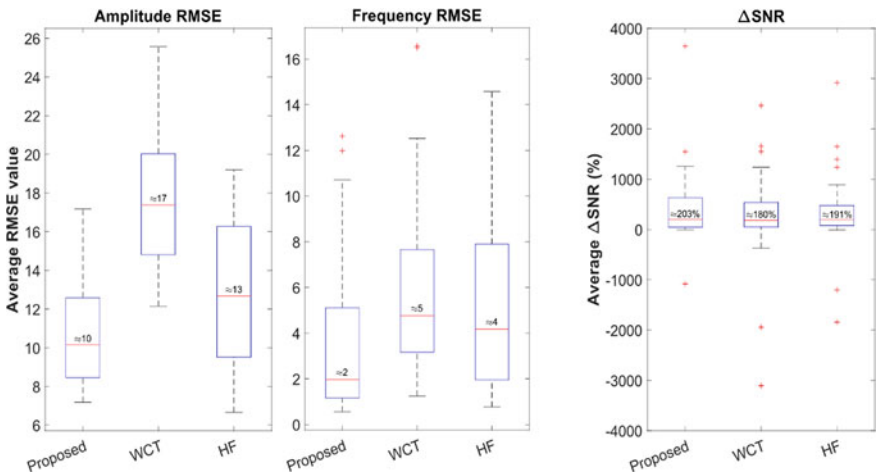
The result does not conflict with the authors' hypothesis. However, we should conduct a few more statistical studies to fully evaluate the effectiveness of this method or compare its effectiveness with other methods about the ocular artifact removal.

Researchers who want to download our source code, feel free to contact us for further instruction and getting a link to download the code.





**Fig. 6** The full result of our proposed method, including corrected data and estimated EOG artifact component



**Fig. 7** The distribution of RMSE value in both time and frequency domain (left) and  $\Delta$ SNR (right) of three methods after applying on the data set

**Table 1** Detail about the RMSE of the methods

Time domain	Mean RMSE	Median RMSE	STD Include outliers
Our method	10.67	10.15	2.66
WCT	17.43	17.38	3.30
HF	12.68	12.69	3.75
Frequency domain	Mean RMSE	Median RMSE	STD Include outliers
Our method	3.32	1.98	3.15
WCT	5.87	4.77	3.67
HF	5.17	4.17	3.77

**Acknowledgements** We acknowledge the support of time and facilities from Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for this study.

**Conflicts of Interest** The authors have no conflict of interest to declare.

## References

1. Fatourehchi M, Bashashati A, Ward RK, Birch GE (2007) EMG and EOG artifacts in brain computer interface systems: a survey. *Clin Neurophysiol* 118:480–494
2. Chang W-D, Cha H-S, Kim K, Im C-H (2016) Detection of eye blink artifacts from single prefrontal channel electroencephalogram. *Comput Methods Programs Biomed* 124:19–30
3. Issa MF, Juhasz Z (2019) Improved EOG artifact removal using wavelet enhanced independent component analysis. *Brain Sci* 9:355
4. Joyce CA, Gorodnitsky IF, Kutas M (2004) Automatic removal of eye movement and blink artifacts from EEG data using blind component separation. *Psychophysiology* 41:313–325
5. Klados MA, Papadelis C, Braun C, Bamidis PD (2011) REG-ICA: a hybrid methodology combining blind source separation and regression techniques for the rejection of ocular artifacts. *Biomed Signal Process Control* 6:291–300
6. Bizopoulos PA, Al-Ani T, Tsalikakis DG, Tzallas AT, Koutsouris DD, Fotiadis DI (2013) An automatic electroencephalography blinking artefact detection and removal method based on template matching and ensemble empirical mode decomposition. In: 2013 35th annual international conference of the IEEE engineering in medicine and biology society (EMBC)
7. Yong X, Fatourehchi M, Ward RK, Birch GE (2012) Automatic artefact removal in a self-paced hybrid brain-computer interface system. *J Neuroeng Rehabil* 9:50
8. Krishnaveni V, Jayaraman S, Malmurugan N, Kandaswamy A, Ramadoss K (2004) Non adaptive thresholding methods for correcting ocular artifacts in EEG. *Acad Open Int J* 13
9. Mannan MMN, Kamran MA, Kang S, Jeong MY (2018) Effect of EOG signal filtering on the removal of ocular artifacts and EEG-based brain-computer interface: a comprehensive study. *Complexity* 2018
10. Klados MA, Bamidis PD (2016) A semi-simulated EEG/EOG dataset for the comparison of EOG artifact rejection techniques. *Data Brief* 8:1004–1006
11. Lins OG, Picton TW, Berg P, Scherg M (1993) Ocular artifacts in EEG and event-related potentials I: Scalp topography. *Brain Topogr* 6:51–63
12. Libenson MH (2012) Practical approach to electroencephalography E-Book. Elsevier Health Sciences