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Establishing best practices in photoplethysmography signal acquisition and processing

# Establishing best practices in photoplethysmography signal acquisition and processing

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Abbreviated Title: Best practices in photoplethysmography

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## Abstract

Photoplethysmography is now widely utilised by clinical devices such as pulse oximeters, and wearable devices such as smartwatches. It holds great promise for health monitoring in daily life. This editorial considers whether it would be possible and beneficial to establish best practices for photoplethysmography signal acquisition and processing. It reports progress made towards this, balanced with the challenges of working with a diverse range of photoplethysmography device designs and intended applications, each of which could benefit from different approaches to signal acquisition and processing. It concludes that there are several potential benefits to establishing best practices. However, it is not yet clear whether it is possible to establish best practices which hold across the range of photoplethysmography device designs and applications.

## Key terms

photoplethysmogram, pulse wave analysis, signal processing, wearables

## Establishing best practices in photoplethysmography signal acquisition and processing

1  
2  
3 1 This Editorial considers whether it would be possible and beneficial to establish best practices  
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5 2 for acquiring and processing photoplethysmography signals.  
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8 3 Photoplethysmography is an optical technique which provides non-invasive measurements of  
9  
10 4 the arterial pulse wave, which is related to the blood volume change in the observed microvascular  
11  
12 5 tissue. The photoplethysmogram (PPG) signal is already widely utilised by clinical devices such as pulse  
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14 6 oximeters (1), and wearable devices such as smartwatches (2). Photoplethysmography holds great  
15  
16 7 promise for health monitoring in daily life. Indeed, several potential applications of  
17  
18 8 photoplethysmography were presented in 2021 alone in *Physiological Measurement*, including: blood  
19  
20 9 pressure monitoring (3, 4); detecting peripheral arterial disease (5); sleep staging (6); screening for  
21  
22 10 sleep apnea and cardiovascular disease (7, 8); and detecting driver sleepiness (9).  
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26  
27 11 Despite the widespread use of photoplethysmography, best practices have not yet been  
28  
29 12 established for acquiring and processing photoplethysmography signals. This may in part be due to  
30  
31 13 the diversity of photoplethysmography device designs, ranging from smartwatches to earbuds, and  
32  
33 14 applications, ranging from oxygen saturation measurement in clinical practice to heart rate monitoring  
34  
35 15 during exercise (10). Potentially, the best approach to signal acquisition and signal processing could  
36  
37 16 differ between each device design and application. Nonetheless, there could be benefits to  
38  
39 17 establishing best practices, such as establishing hardware configurations that consistently provide  
40  
41 18 high quality signals, and establishing signal processing algorithms that can accurately derive  
42  
43 19 parameters from a variety of PPG signals. This is illustrated by the findings of Liu *et al.* in their recent  
44  
45 20 article in *Physiological Measurement*. They found that the use of different PPG signal filtering settings  
46  
47 21 can result in different measurements being obtained from PPG pulse wave analysis. Based on this,  
48  
49 22 they highlighted the potential benefits of the 'standardisation' of PPG filtering (11). In this case,  
50  
51 23 establishing best practices for filtering PPG signals would have the benefit of allowing pulse wave  
52  
53 24 indices to be compared between studies and between devices. However, this may not be  
54  
55 25 straightforward as different filtering settings may be required for different applications, such as heart  
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rate monitoring (which uses the fundamental frequency of the PPG,  $\approx 0.5\text{-}3\text{Hz}$ ) and blood pressure assessment (which uses higher frequency content).

Potential areas in which best practices could be established include factors relating to device design (hardware and software) and measurement protocols (recording setting and duration). These are summarised in Figure 1, and now described.

### Establishing best practices in photoplethysmography signal acquisition and processing



**Figure 1:** Factors influencing photoplethysmography measurements, and important advances towards establishing best practices.

Source: This Max Health Band image has been obtained by the authors from the [Wikimedia website](#) where it was made available by Peter H Charlton under a [CC BY 4.0 licence](#). It is included within this article on that basis. It is attributed to Peter H Charlton.

Several factors in the hardware design influence the PPG signal (2, 12), and are therefore potential areas in which best practices could be established. Firstly, the wavelength of emitted light determines the depth of light penetration, and consequently the level of the vasculature contributing to the PPG signal (13), which influences signal quality (14). Current best practice is to use longer wavelengths (*e.g.* infrared) for transmission photoplethysmography as these penetrate deeper (15), and shorter wavelengths (*e.g.* green) for reflectance photoplethysmography as these produce higher signal quality for heart rate measurement (17). However, this practice may need to be revisited as the

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2  
3 44 use of green light has been found to result in less accurate heart rate monitoring in subjects with  
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5 45 darker skin tones (19). Secondly, in reflectance photoplethysmography the signal quality is influenced  
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7 46 by the geometry of the light emitter, light detector, and sensor casing. Current best practice is to  
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9 47 design the surrounding casing to eliminate ambient light as far as possible (18). In the future this may  
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11 48 be extended to using geometries in which the LED surrounds the photo detector, as these have been  
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13 49 found to give higher signal quality (16). Thirdly, the contact pressure applied by the device to the skin  
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15 50 impacts the shape of the PPG pulse wave (20) and consequently its second derivative (21). Best  
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17 51 practice in the area of contact pressure has not yet been established: higher pressures may reduce  
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19 52 probe-tissue movement artifact, and have been found to increase the accuracy of PPG-based heart  
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21 53 rate monitoring (22). However, it is not clear whether such pressures would be suitable for long-term  
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23 54 monitoring. Ideally, the contact pressure should remain constant when analysing pulse wave shape,  
24  
25 55 such as when tracking changes nocturnal changes in blood pressure (23). Fourthly, the body site  
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27 56 chosen for PPG measurement influences pulse wave shape (27), and the utility of the acquired signal  
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29 57 (2). Best practice has not yet been established in this area: in clinical devices the finger is often used  
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31 58 (29), whereas in consumer devices the wrist is often used due to user preference (24). In summary,  
32  
33 59 the challenge of establishing best practices is not trivial, as several factors can influence the PPG signal,  
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35 60 and it is likely that different device configurations would be best suited to different applications.  
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42 The software used in PPG devices influences the PPG signal and the parameters derived from  
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44 62 it, and therefore presents potential areas in which to establishing best practices. Firstly, there is a  
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46 63 compromise between increasing the sampling frequency to capture details of the shape of PPG pulse  
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48 64 waves, and reducing it to reduce power consumption (30). Best practices differ between applications,  
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50 65 with minimum acceptable sampling frequencies of 10, 16, and 25 Hz reported for heart rate,  
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52 66 respiratory rate, and pulse rate variability measurements respectively (25), (26), (28). Secondly,  
53  
54 67 different approaches can be used to remove motion artifact, ranging from eliminating periods of  
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56 68 motion (31), to denoising the PPG (32), to cancelling motion artifact using a reference accelerometer  
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Establishing best practices in photoplethysmography signal acquisition and processing

69 or gyroscope signal (33). Here, best practices also differ between applications: in hospital monitoring  
70 it has been proposed that periods of motion should be eliminated from analyses (40), whereas in  
71 exercise monitoring the alternative approaches of denoising the PPG or cancelling motion artifact are  
72 used (32). Whilst it may be challenging to develop a universal strategy to PPG signal quality  
73 assessment, recent work has demonstrated that a single approach can perform well across different  
74 heart rhythms and different PPG devices (42). Thirdly, the analog and digital filtering used to pre-  
75 process signals influences both the amplitudes and timings of PPG pulse wave features (11, 34). For  
76 instance, an optimal low-pass filter cut-off of 6 Hz has been proposed to preserve the higher harmonic  
77 components of the PPG, and minimise variability in indices calculated from its second derivative (35).  
78 Fourthly, the choice of signal processing algorithm used to estimate a physiological parameter from  
79 the signal can greatly influence the accuracy and precision of the parameter (36). Best practices for  
80 deriving pulse wave features from finger PPG signals have been proposed (37, 38). However, best  
81 practices have not yet been established for signals acquired at the wrist, which differ from finger  
82 signals (39). Similarly, it could be beneficial to optimise neural network architectures for PPG analyses,  
83 building on existing architectures (6). Further work is also required to identify the best pulse wave  
84 features for different tasks from amongst the wide range of features proposed in the literature (41,  
85 43). For instance, recent studies have investigated the best features for blood pressure estimation (3)  
86 and pulse rate variability analysis (44). The best algorithm design may also depend on a subject's  
87 characteristics, as shown by recent proposals of different blood pressure estimation algorithms for  
88 subjects of different ages (45) and subjects of different blood pressure categories (46). In summary, it  
89 may be difficult to establish best practices for the software used in PPG devices, as the best approach  
90 may vary according to the sensor configuration, application, and subjects being monitored.

91 A further area in which best practices could be established is the protocols used to obtain PPG  
92 measurements, where best practices could be used to obtain repeatable and reproducible  
93 measurements. Measurement protocols can be tightly controlled in clinical settings, where



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2  
3 94 consideration can be given to room temperature, subject position, and the duration of rest prior to  
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5 95 measurement (47). However, protocols cannot be so tightly controlled when obtaining measurements  
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7 96 from consumer devices in daily life. Nevertheless, measurements can be obtained in a repeatable  
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9 97 manner during periods of rest, such as resting and night-time resting heart rates (48) (49). Future work  
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11 98 may consider the required recording durations and acceptable levels of signal quality to estimate  
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13 99 different physiological parameters from the PPG (50). Whilst it is possible to obtain some parameters  
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15 100 during exercise (*e.g.* heart rate) (32), it may only be possible to obtain other parameters accurately  
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17 101 whilst at rest (*e.g.* those derived from the second derivative of the PPG, such as the aging index) (51).  
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22 102 It is clear that there are several potential areas in which best practices could be established  
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24 103 for the acquisition and processing of PPG signals. However, it is not yet clear whether it would be  
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26 104 possible and beneficial to establish best practices. On the one hand: it may not be possible to establish  
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28 105 best practices as they may vary greatly between device designs and applications; it may not be  
29  
30 106 possible to use them widely if they are patented; and, they may not be beneficial if they don't  
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32 107 substantially improve device performance. On the other hand, establishing best practices could:  
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34 108 reduce the time taken to design and manufacture devices; ensure PPG-based measurements are as  
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36 109 accurate and reproducible as possible; and, help advance the field as researchers and developers  
37  
38 110 could build on existing best practices when making novel developments.  
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43 111 Several advances could aid research into determining whether it would be possible and  
44  
45 112 beneficial to establish best practices for PPG signal acquisition and processing. Firstly, wearable  
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47 113 devices which provide the raw PPG signal are invaluable for such research, as demonstrated through  
48  
49 114 the use of the Empatica E4 wristband in many research studies (52). Whilst several research devices  
50  
51 115 can provide the raw PPG signal (10), large-scale studies could be conducted more easily in daily life if  
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53 116 consumer devices were similarly able to provide raw PPG signals. Secondly, freely available datasets  
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55 117 allow researchers to benchmark their own PPG signal processing algorithms against others on a  
56  
57 118 common dataset. Several such datasets are available (10), including: the WeSAD and PPG-DaLiA  
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Establishing best practices in photoplethysmography signal acquisition and processing

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3 119 datasets, acquired using an Empatica E4 device in healthy subjects (53) (54); and the VitalDB and the  
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5 120 MIMIC Waveform databases, acquired from critically-ill patients (55, 56). However, there are  
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7 121 limitations to current datasets: they are often collected from either healthy volunteers or a particular  
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9 122 patient population, rather than a broad cross-section of society; they often contain PPG signals  
10  
11 123 acquired by only one device, rather than signals acquired using different hardware configurations; and  
12  
13 124 they are often recorded in either laboratory or clinical settings, but few are recorded in daily life.  
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15 125 Thirdly, there is a need for widely accepted validation protocols with which to assess the performance  
16  
17 126 of PPG-based devices. Such protocols already exist for devices measuring blood pressure and heart  
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19 127 rate (57) (58). However, different standards may be required for different applications, such as varying  
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21 128 the accuracy and data availability thresholds according to the intended use case and measurement  
22  
23 129 scenario (59, 60).

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28 130 To conclude, there are several potential benefits to establishing best practices for acquiring  
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30 131 and processing PPG signals. However, it is not yet clear whether it is possible to establish best practices  
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32 132 which hold across the range of PPG device designs and applications. Therefore, much further work is  
33  
34 133 required to investigate whether it would be possible and beneficial to establish best practices, and to  
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36 134 understand how they may differ between device designs and intended applications.  
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