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Validation of a photoplethysmographic heart rate monitor: Polar OH1

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The Laboratories ACTES (EA3596) and EPSI (EA4660) conducted this study independently and unbiased for Polar Electro Oy.

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36 **Abstract**

37 This study assessed the validity of a photoplethysmographic heart rate (HR) monitor, the
38 Polar OH1 in various sports performed in ecological conditions: running, cycling, soccer,
39 kayaking, walking, tennis and fitness. Seventy trained athletes (56 males, 14 females) wore
40 the Polar OH1 armband and the H7 chest belt during training. A total of 390 hours and 38
41 minutes of recording were compared using a 20-bpm window to assess dataquality, and
42 Bland-Altman agreements and ICC analyses to test accuracy. Linear regression analyses
43 evaluated the HR accuracy and correlation with skin tone. Training loads (TRIMPs) were
44 compared for each session. Reliability was high for endurance sports (>99%) and lower for
45 sports involving arm movements (92~95%). Biases were slightly negative for all sports,
46 whereas widths of limits of agreement varied from 7 to 20bpm. Bland&Altman agreements
47 were all under 5 % except tennis, kayak and fitness. HR accuracy was positively correlated to
48 skin tone ($p<0.05$). Finally, TRIMPs from OH1 device were inferior to criterion's (except
49 walking and soccer), within a 3% range from reference. Hence, OH1 represents a valid tool to
50 monitor instantaneous HR and training load, especially for endurance sports.

51

52

53

54 INTRODUCTION

55 Over the past decades, heart Rate Monitor (HRMs) have become popular tools for training
56 guidance and physical activity monitoring [1,2] . These devices are regularly upgraded with
57 improving technology (GPS integration, inertial sensor, memory) to respond to user
58 requirements [3]. The first commercial HRMs based heart rate (HR) measurement on thoracic
59 electrical measurement using chest belts to obtain ECG signal transduced in bursts when R
60 peaks occur. More recently, manufacturers have equipped their devices with a
61 photoplethysmography (PPG) system behind the wrist clock, as chest belts are less convenient
62 for women and less hygienic.

63 Photoplethysmography was first used in the late 1930s [4] especially in the medical field for
64 measuring HR, O₂ saturation and cardiac output [5]. In brief, a diode emits a single
65 wavelength light which is propagated through the tissue of interest and then is captured by a
66 distant detector. The analysis of the temporal difference between the signal source and
67 collection provides the required information.

68 PPG is mainly used with two light wavelengths. Red light is common in medical and hospital
69 technologies, whereas green LEDs have gained popularity for consumer products. Compared
70 to red light, they show higher sensitive to skin melanin and shallower data acquisition but
71 much greater affinity to oxyhemoglobin and deoxyhemoglobin [6], which means better
72 accuracy in HR monitoring [7]. Green light monitors are therefore less subject to movement
73 artifacts than red light monitors [8], and the low cost of green light technology has gradually
74 made them available to the general public, especially for HR-monitored activities, like
75 exercise and sports activities. Major brands have developed wrist-worn watches designed for
76 both recreational and trained athletes, integrating an optical HR (OHR) monitor in the watch
77 case, to replace the traditional chest belt. The HR values of OHR are insufficiently accurate
78 [9–13], despite recent improvements in the number of usable light emitters and the built-in
79 algorithms [14,15]. Among the many reasons are mainly low skin temperature [16], motion
80 artifacts [16,17], inadequate attachment or positioning [13,16,18], skin type [14,15], activity
81 type [19] and intensity of exercise [9,19,20]. Another reason is the number of LED sources:
82 most of brands use two or three light sources, which may be insufficient to retrieve blood
83 flow data, especially through the bony wrist region, more sensitive to motion artifacts [17].

84 Most of the aforementioned studies validating OHR monitors were performed in laboratory or
85 controlled environments like sports gyms [9,14,15,21,22], using standardized protocols of
86 low-to-medium intensity and limited duration (typically <1 hour) [9,15,21–23]. From a more
87 training-centered perspective, these systematic protocols might not be valid for use in

88 ecological conditions, i.e., outdoor or with varying intensities and durations, for team sports
89 (e.g., soccer) or endurance sports (e.g., running and cycling) at regional or national levels
90 requiring daily training load monitoring [16].

91 The accuracy and reactivity of these devices are essential to HR measurement. Currently, HR
92 measures are mainly used to calibrate training intensity with real-time HR values and
93 calculate training load [1,2]. In the first case, athletes use the HR on the wrist display to adjust
94 speed or other mechanical variables. Hence, accuracy and reactivity are both important for
95 proper intensity calibration. In the second case, collected HR values are computed with
96 various methods to obtain a global training load, such as TRIMP by Banister et al. [24,25],
97 which remains the gold standard. Inaccurate HR measurement yields incorrect TRIMP
98 calculation [24,26], which means that race day fitness level and fatigue are also likely to be
99 incorrectly assessed [24,27].

100 Recently, Polar Electro Oy (Kempele, Finland) developed a 6-LED wrist clock (M600)
101 producing a valid HR signal in most (controlled) conditions [14]. Nevertheless, Horton et al.
102 point out that activities like weight lifting, muscle and ligament tension in the wrist may
103 interfere with HR detection from capillary blood flow [14]. More recently, the same
104 manufacturer designed an autonomous 6-LED OHR sensor, the OH1, that can be strapped
105 around the arm or forearm and is potentially less subject to the motion artifacts of wrist-worn
106 watches. Its use was validated for moderate-intensity sports activities [21].

107 The aim of this study is (1) to assess the accuracy of the HR signal in trained athletes
108 wearing Polar OH1 monitor in ecological conditions during outdoor activities, including team
109 and endurance sports, compared to traditional chest belt (Polar H7, Polar, Electro Oy,
110 Kempele, Finland), and (2) to compare training load obtained from the HR calculation
111 provided by the two devices.

112

113 **METHODS**

114 **Subjects.** 70 subjects, 56 males and 14 females, participated in this study. All were in good
115 physical condition and exercised regularly, from 5 to 20 hours per week, during personal free
116 time or with a club. Mean (\pm SD) age, height and body mass of all participants were 19.7 ± 5.8
117 yrs, 174.4 ± 10.5 cm, and 66.9 ± 12.1 kg, respectively. The skin types of athletes living in
118 Burgundy (France, 23 participants) and the West Indies (47) were assessed with the
119 Fitzpatrick skin scale [28], from 1 (lightest tone) to 6 (darkest).

120

121

122 **Experimental protocol and data collection.**

123 Participants followed their usual training routine following coaches' instructions. Running,
124 biking and walking were performed on various terrains, switching between flats, hills and
125 downhills, which induced a wide HR spectrum from low to high. Tennis, crossfit and soccer
126 were performed on flat ground or in water, but also showed low and high HRs due to
127 successive pauses and sudden accelerations or repetitions.

128 For each session, participants wore two HR monitors: the Polar OH1 monitor and the Polar
129 H7 belt (Polar Electro Oy, Kempele, Finland) as the criterion measurement [12,29], paired
130 with a Polar M400 watch. Following the manufacturer's instructions, the OH1 device was
131 strapped around the upper arm, firmly enough to remain in place but not enough to obstruct
132 blood flow. Recordings for both were started at rest before the exercise start and terminated
133 after a short recovery time. Procedures were conformed ethics in sport and exercise science
134 [30].

135

136 **Data processing and statistical analyses.**

137 HR data from both M400-H7 and OH1 were retrieved from the Polar Flow web service,
138 visually inspected for criterion dysfunction, discarded when necessary, and exported as
139 spreadsheets. For comparisons of each measurement session, signals were synchronized with
140 the least square method and smoothed on a 10-s window.

141 First, OHR quality was defined as the percentage of data within ± 20 bpm of the Polar H7
142 signal (OH1-IN), with data outside this range labeled OH1-OUT. Second, OHR accuracy was
143 assessed with Bland-Altman analysis [31] to test agreement between OH1 and H7 data: bias
144 (mean difference, MD), standard deviation (SD) and upper and lower limits of agreement
145 (LOA, defined as $MD \pm SD$) were calculated. Last, minimal, maximal and average HRs were
146 calculated and training load values were computed following Banister's modified TRIMP
147 [26], using theoretical or measured rest and maximal HRs. Intraclass correlation coefficients
148 (ICCs) [32] were computed using OH1 and H7 data for each sport: their value indicates the
149 reliability of the OH1 measures vs. criterion (<0.5 : poor, $0.5-0.75$: moderate, $0.75-0.9$: good,
150 >0.9 : excellent) [33].

151 For the skin tone effect on HR accuracy, linear regressions established potential correlations
152 between these discrete quantitative values and biases. All parameters including the training
153 loads obtained from the OH1 and H7 sensors from each session were compared using Student
154 tests. A p-value <0.05 was considered significant.

155

156 **RESULTS**

157 Examples of the simultaneous HR recordings from the H7 and OH1 are presented in Figure 1;
158 the right figure illustrates the dropout phenomenon outside the 20-bpm criterion zone.

159 In all, 390 hours and 38 minutes of recordings were analyzed (cycling: 113hr,49min;
160 running:102hr,26min; soccer: 47hr,45min; kayaking: 50hr,41min; walking: 37hr,30min;
161 tennis: 18hr,35min; and fitness: 19hr,53min), distributed across 233 sessions. Differences in
162 sports durations were mainly due to the much longer duration of walking and cycling sessions
163 (up to several hours). Results are compiled in Table 1.

164 Sports involving more vigorous upper limbs movements (kayak, tennis and fitness) exhibited
165 wider LOAs than endurance sports (cycling and running), whereas biases were not impacted
166 by activity type (Fig. 2 and Table 1). ICCs for all sports were above 0.99 (Table 1), indicating
167 the excellent reliability of OH1 data vs. criterion.

168 The mean value of skin type was 3.4 ± 2.2 and it affected bias and LOAs. The correlation
169 between skin tone and bias was positive ($p<0.001$), i.e., accuracy (bias) was decreased with
170 darker skin.

171 Training loads were not different in walking and soccer, but they were systemically higher
172 with the criterion H7 monitor for other sports (Table 2).

173

174

175 **DISCUSSION**

176 Although most studies have sought to validate similar HR devices in a laboratory
177 environment, our research was based on data collected in real-life situations by athletes
178 following their training routines in various type of activities.

179 Our first result was the difference in the proportion of data outside the threshold limits – i.e.,
180 20 bpm from criterion value (OH1-OUT) – between the arm-driven sports (tennis, kayaking
181 and fitness) and non-arm-driven sports. The latter showed a very high percentage of useful
182 values in endurance sports like walking, running and cycling, whereas the upper-body based
183 sports presented a much higher error rate (Fig. 1B and 1C, Table 1). In the absence of
184 dedicated tools to assess this imprecision, we can only assume that this was due to motion
185 artifacts from the arm and chest movements, as reported by others [12,14,16]. As a corollary,
186 these three sports also provided the widest LOAs, yet still less than those of the same brand
187 wrist-worn model [14]. Nevertheless, the OH1 provided less than 1% data out of threshold in
188 the traditional endurance sports (cycling, running, walking) and soccer (Table 1), which
189 represents a very decent number for athletes and coaches relying on HR data. Although the

190 algorithm to extrapolate HR remains Polar-proprietary, we can nevertheless assume that the
191 6-LED system provides reliability superior to that of the traditional 2- or 3-LED devices
192 [14,15]: subcutaneous blood information transmitted and collected through six light sources
193 and captors is centrally analyzed, and therefore erroneous data is better detected and
194 discarded. From the synchronized HR signals, we also note that the OH1 HR values were
195 regularly slow to increase or decrease during intensity variations (Fig. 1C). Technically, this
196 phenomenon can be related to delays in microvascular blood flow increases or the smoothing
197 filters integrated into the OH1 device to avoid large errors in HR measurement. Hence, in
198 intermittent exercise, this phenomenon can enlarge LOAs because of the shift in
199 instantaneous HR values collected by the two systems.

200 In addition, as noted above, the sports showed discrepancies. Sports involving active use of
201 arms (tennis, fitness, kayaking) led to decoupling mainly in the transitions from low to high
202 HR, for example during acceleration (Fig. 1B), and several minutes might have been
203 necessary for the system to readjust properly. A similar phenomenon was recently observed in
204 more controlled conditions with another wristwatch from the same brand [14]. On a side note,
205 a non-negligible number of recordings could not be analyzed due to criterion dysfunction,
206 mostly in kayaking, as vigorous chest movements impaired HR detection by the H7 belt. As
207 the standardized positioning of the OH1 on the upper arm also presented motion artifacts, it
208 might be better to strap it to body limb less subject to data collection failure.

209 Similarly, biases were systematically greater in arm-driven sports, though they remained
210 under 1 bpm and negative, implying that the OH1 measures a (very slightly) lower HR than
211 the criterion (Table 1), as noted by others [14,19,21,34] or not [16,35]. They also had larger
212 Bland-Altman agreements, although just above 5% for tennis and kayaking.

213 Mean HRs measured by the OH1 were lower for all sports except walking and soccer, but the
214 difference was limited to a gap less than 1 bpm (Table 1), as observed for other devices
215 [18,19]. Yet, the minimal and maximal measured HR values showed no difference, and these
216 undervalued data are still reliable markers in detecting overtraining risks [1]. Therefore,
217 differences in mean HR could lead to errors in the computation of training load, as athletes
218 and coaches collect and analyze these valuable data to assess fitness peaks and tapering
219 periods [36]. Indeed, according to the HR data, the TRIMP values extrapolated from the OH1
220 device were lower than those of the criterion (Table 2) except for walking and soccer, but the
221 difference remained small, from 3 % for kayaking to 0.7 % for cycling. Therefore, OH1
222 TRIMP may be used for training endurance athletes (cyclists and runners), who mostly use it

223 in their training program[26]. To our knowledge, no studies on OHR have focused on training
224 loads for confirmed athletes. Overall, the ICCs confirmed the excellent correlations between
225 OH1 and criterion HR for all sports studied here (Table 1).

226
227 Interestingly, at times the OH1 provided apparently trustworthy when criterion failed. For
228 example, several kayaking recordings were discarded because of Polar H7 dysfunction
229 underwater (rolling) or during higher exercise intensities (maximal or submaximal intervals)
230 when the H7 belt did not remain properly strapped around the chest [37]. The same
231 observation were made in swimming, and OH1 accuracy should be evaluated in aquatic sports
232 against a validated criterion [38]. Similarly, when soccer players chested the ball, it
233 occasionally displaced the HR belt and disrupted HR data, whereas the OH1 provided
234 accurate HR values (Table 1).

235 Our large and various sample from the West Indies and Burgundy enabled us to compare the
236 effect of skin tone on HR accuracy. As have other studies, our study confirms that biases
237 become larger with darker skins [9,15], though this was negligible. Nevertheless, the biases
238 were notably very low in soccer, where more than 90% of players (Table 1) from the West
239 Indies exhibited values on Fitzpatrick skin scale equal to or above 5, which does not agree
240 with previous conclusions [9,15]. A plausible explanation might be West Indies' hot and
241 humid climate, which could have induced greater peripheral vasodilation [39], thereby making
242 the blood signal more accessible to the OH1 sensor, regardless of skin tone.

243 This device is also useful for daily heart rate monitoring in patients to assess, for example,
244 daily energy expenditure [40], particularly in overweight and pregnant women, whose
245 tolerance and acceptability of chest strap constriction are lower [41]. An OHR device strapped
246 around the arm or forearm would supposedly be better tolerated.

247 In conclusion, the Polar OH1 was worn by athletes and studied in field conditions. It showed
248 good overall reliability for all activities, especially traditional endurance sports like running
249 and cycling. It might therefore be a reliable alternative to constrictive chest strap for regular
250 and intensive training. In that matter, multiple emitters (6 in the Polar OH1) certainly play a
251 key role. However, sports implying chest and arm movements induce a higher rate of errors
252 and heart rate dropouts. In the future, studies will be needed to assess its accuracy for water
253 sports, and interesting potentialities should be explored in health tracking.

254

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- 356

357 **Captions**

358 **Figure 1**

359 Examples of HR recordings of Polar H7 (dashed black line) and OH1 (solid grey line) in
360 cyclic (left) and non-cyclic (right). Whereas both signals are mostly identical in running
361 (panel A), Polar OH1 may show a decoupling signal out of the threshold limits (HR dropout,
362 arrow, panel B), in non-cyclic sports (here, kayaking). Panel C illustrates another minor
363 decoupling phenomenon (arrow), potentially impacting values of minimum, maximum and
364 mean HR and therefore TRIMPs.

365

366 **Figure 2**

367 Bland-Altman plots of HR_{OH1} and HR_{H7} signals for cycling (left) and tennis (right), with bias
368 (thick-dashed black line) and lower and higher values of agreement (thin-dashed black lines).

369

370 **Table 1**

371 Session durations, percentage of values out of the 20bpm threshold zone (OH1-OUT), minimum / maximum / mean HR values, bias and LOAs,
 372 Bland & Altman (B&A) agreements, intraclass correlation coefficients (ICC) of Polar OH1 and H7 data.
 373 Difference H7 vs. OH1: *P < 0.05, **P < 0.01, ***P < 0.001.

Activity	Analyzed duration (min)	OH1 - OUT (%)	H7			HR (bpm)			Bias (bpm)	LOA (bpm)		B&A agreement	ICC
			Min	Max	Mean	Min	Max	Mean		Lower	Upper		
Cycling	3355	0.31%	81.3 ± 12.9	162.3 ± 18.1	132.2 ± 25.8	81.6 ± 13.6	162.2 ± 18.2	132.3 ± 25.6*	-0.08	-3.74	3.59	4.63%	0.999
Running	2972	0.93%	94.1 ± 16.3	180.2 ± 15.2	152.1 ± 28.3	94.8 ± 16.9	180.0 ± 15.2	151.8 ± 13.7***	-0.37	-4.96	4.21	4.88%	0.998
Walking	1124	0.07%	64.2 ± 5.3	109.6 ± 19.4	80.6 ± 9.2	63.7 ± 5.8	110.1 ± 19.0	80.4 ± 9.2	-0.18	-3.67	3.32	4.84%	0.996
Tennis	508	8.81%	92.1 ± 13.2	186.0 ± 13.1	152.3 ± 12.5	92.5 ± 13.4	184 ± 11.8**	151.3 ± 12.3*	-0.83	-7.53	5.87	5.79%	0.995
Kayak	1450	4.65%	87.0 ± 22.9	171.1 ± 24.9	121.5 ± 25.5	86.8 ± 23.4	167.6 ± 26.8	120.6 ± 25.4**	-0.68	-8.81	7.45	5.17%	0.995
Fitness	545	8.64%	74.8 ± 11.3	172.9 ± 19.1	124.4 ± 15.9	77.1 ± 12.9	170.7 ± 18.5	123.6 ± 15.8**	-0.74	-11.08	9.6	8.68%	0.992
Soccer	1430	0.19%	83.2 ± 15.2	189.3 ± 19.5	132.6 ± 17.2	83.5 ± 15.5	189.3 ± 19.5	132.5 ± 17.3	-0.08	-4.56	4.39	4.90%	0.999

374 Mean ± SD

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382 **Table 2**

383 TRIMP values for each sport, and their mean differences on each session.

384 Difference H7 vs. OH1: *P < 0.05, **P < 0.01, ***P < 0.001.

Activity	TRIMP (n.u.)		Difference (%)
	H7	OH1	
Cycling	44.55 ± 76.32	44.49 ± 76.25 *	0,67 ± 0,93
Running	74.86 ± 42.69	74.38 ± 42.46 ***	0,71 ± 0,98
Walking	18.53 ± 12.87	18.38 ± 12.88	---
Tennis	65.61 ± 28.25	64.63 ± 28.72 *	1,90 ± 2,39
Kayak	29.35 ± 12.79	28.88 ± 12.94 **	3,01 ± 3,17
Fitness	42.21 ± 23.57	41.50 ± 23.49 *	1,93 ± 1,87
Soccer	71.78 ± 42.00	71.68 ± 42.00	---

385 Mean ± SD

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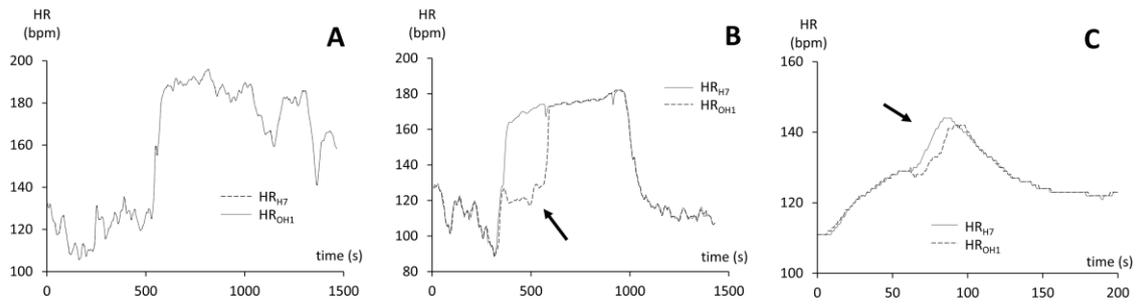


Fig. 1

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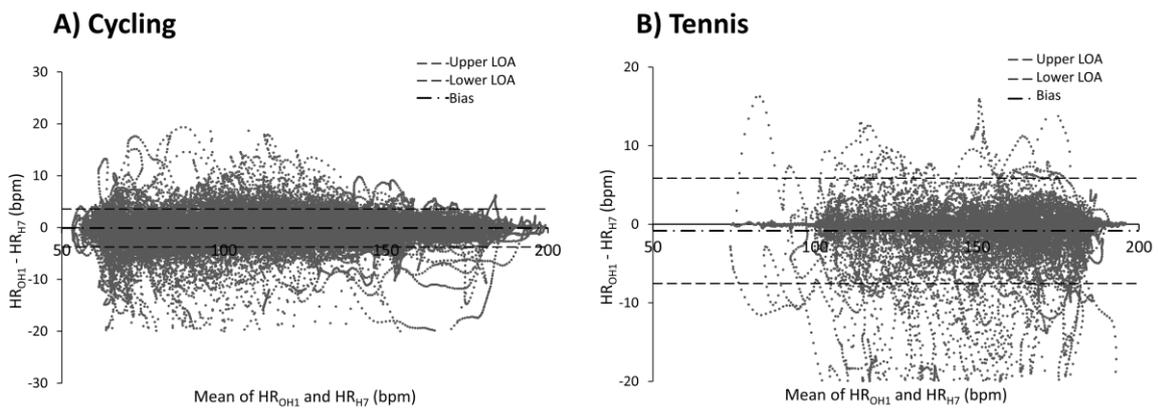


Fig. 2

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