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Utility of the Photoplethysmogram in Circulatory Monitoring

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The *photoplethysmogram* is a noninvasive circulatory signal related to the pulsatile volume of blood in tissue and is displayed by many pulse oximeters and bedside monitors, along with the computed arterial oxygen saturation. The photoplethysmogram is similar in appearance to an arterial blood pressure waveform. Because the former is noninvasive and nearly ubiquitous in hospitals whereas the latter requires invasive measurement, the extraction of circulatory information from the photoplethysmogram has been a popular subject of contemporary research. The photoplethysmogram is a function of the underlying circulation, but the relation is complicated by optical, biomechanical, and physiologic covariates that affect the appearance of the photoplethysmogram. Overall, the photoplethysmogram provides a wealth of circulatory information, but its complex etiology may be a limitation in some novel applications.

THE *photoplethysmogram* is a noninvasive circulatory signal related to the pulsatile volume of blood in tissue. Pulse oximeters, which compute fractional arterial oxygen saturation (Sao_2) using photoplethysmography with at least two different light wavelengths, often display a photoplethysmogram to help clinicians distinguish between reliable Sao_2 measurements (associated with clean, physiologic waveforms) and unreliable measurements (associated with noisy waveforms). The photoplethysmogram is cosmetically similar to an arterial blood pressure waveform (ABP). Because the former is noninvasive and nearly ubiquitous in hospitals, it is intuitive to seek circulatory information from the photoplethysmogram, and the extraction of circulatory information from the photoplethysmogram has been a popular subject of contemporary research.

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Origins of the Photoplethysmogram

Many decades before the advent of pulse oximetry, the simple photoplethysmogram was used as a measure of tissue blood volume.[1] It is related to, but not equivalent to, the measurement of pulsatile tissue volume, plethysmography. Pulsatile tissue volume can be directly measured, *e.g.*, placing a strain gauge that measures changes in the circumference of an extremity.[2] Plethysmography measures the sum total of volume changes in any and all blood vessels (*e.g.*, large and small arteries, arterioles, venules, and veins). Arterial pulsations are the most significant.[3] Capillaries and terminal arterioles are noncompliant,[4,5] with minor beat-to-beat pulsations. Venous oscillations due to respiration and the beating of the right heart may be evident, but many measurement techniques apply enough external pressure to partially or fully collapse veins.

Optical Factors

Complicated optic phenomena distinguish photoplethysmography from plethysmography. In the most common photoplethysmography modality (transmission mode), tissue is irradiated by a light-emitting diode, and light intensity is measured by a photodetector on the other side of the tissue, *e.g.*, across a fingertip or an earlobe. A pulse of blood increases both the optical density and path length through the illuminated tissue (due to intravascular increases of erythrocytes and the light-absorbing hemoglobin they carry), which decreases the light intensity at the photodetector. By convention, the photoplethysmogram is inverted so that it correlates positively with blood volume. Figure 1 is an abstraction of the processes that underlie a photoplethysmogram. Intravascular volume changes comprise the middle row (across the pyramid), whereas the top contains additional optic phenomena that are wavelength dependent. Light intensity is attenuated by oxygenated and deoxygenated hemoglobin (in blood cells), myoglobin (in muscle), and cytochromes, as well as melatonin (in skin) and

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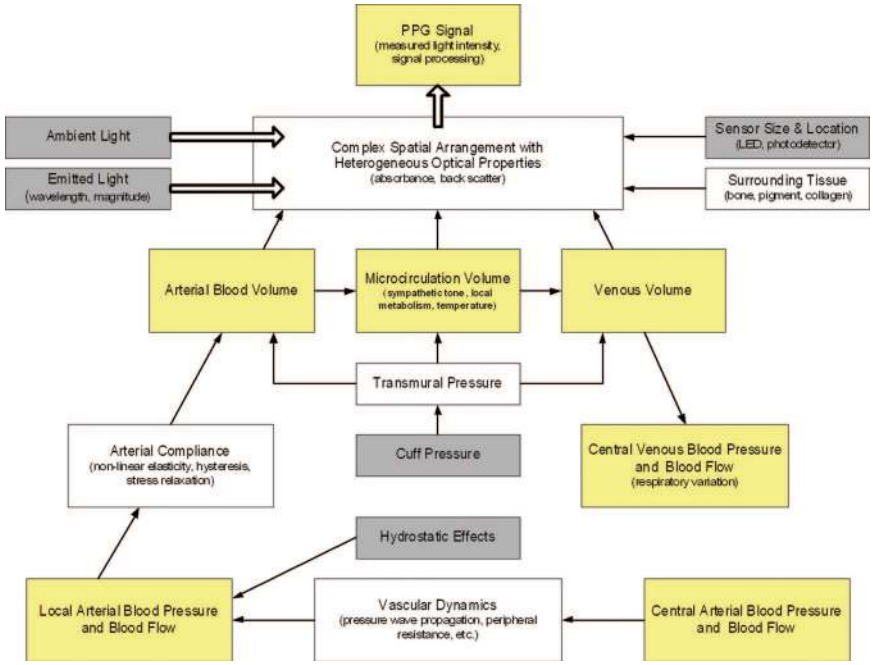

Fig. 1. General processes and interactions that underlie the photoplethysmogram (PPG). *Yellow* indicates simple physiologic parameters. Parameters in *gray* vary with the measurement methodology. LED = light-emitting diode.

other optically significant compounds in bone and connective tissue.[1]

The photoplethysmogram is usually a qualitative measurement, where reductions in light intensity indicate relative increases in blood volume and *vice versa*. The quantitative relation between blood volume, which is distributed throughout an irregular network of vessels, and the fraction of emitted photons that successfully pass through the tissue is complicated. The Beer-Lambert law offers some insight: If a homogenous layer of blood lies perpendicular to a beam of light, light intensity decays exponentially as a function of distance (*i.e.*, % transmission $= 100 * e^{-\alpha lc}$, where α is the absorption coefficient of the material, l is the length of the layer, and c is the concentration of the absorbing material). The Beer-Lambert law only considers light absorption, the major cause of light attenuation, but not other causes of attenuation (scatter, refraction, and reflection). Also, the Beer-Lambert law assumes a simple, homogenous tissue geometry. This approximation may be more reasonable given a relatively uniform, diffuse vascular bed, as in an instrumented earlobe or fingertip. In such common measurement locations, the photoplethysmogram is primarily cutaneous,[6] perhaps arising largely from volume changes in venules that are fed by arteriovenous fistulas.[7,8] However, when the irradiated tissue includes larger, distinct blood vessels, as are found in the forehead, neck, or inguinal canal, the optics are more complex; distinct vessels can alter the photoplethysmogram (as well as the accuracy of pulse oximeters).[9–11] Light propagation through a heterogeneous medium has been subjected to substantial theoretical consideration (*e.g.*, references 12–16). The tissue volume assayed by photoplethysmography does not have precise boundaries: Components along the primary optical path contribute more to the photoplethysmogram, whereas tissue components on the periphery are gradually less significant. The properties of the light-emitting diode (location, size, light intensity, light wavelength) and the photodetector (location, size, photovoltaic properties) further complicate the relation between blood volume and the photoplethysmogram.

It should also be noted that the velocity of blood flow affects the photoplethysmogram, probably because of reorientation and/or packing of erythrocytes that is flow dependent.[17,18] Even in a rigid (*i.e.*, constant volume) glass pipe, oscillating blood flow gives rise to an oscillating photoplethysmogram.[1] There are classic references to photoplethysmography as a flow (rather than volume) measurement (*e.g.*, references 1 and 19), although flow effects may be minor *in vivo*.[1,20–23] It is difficult to sort out the effects of blood flow *versus* volume pulsations *in vivo*.[24]

Reflectance-mode Photoplethysmography

A photodetector can be placed on a tissue's surface alongside the light-emitting diode and record the light that returns back, known as *reflectance-mode photoplethysmography*. Theoretical analysis suggests that, for typical wavelengths, the emitted photons that arrive at the photodetector follow a banana-shaped primary light path through the tissue, barely penetrating deeper than the skin.[22,25,26] *In vitro*, reflectance photoplethysmography can demonstrate a notably different relation with blood volume: The more blood in the vessel, the brighter the photodetector intensity will be. This is because non-

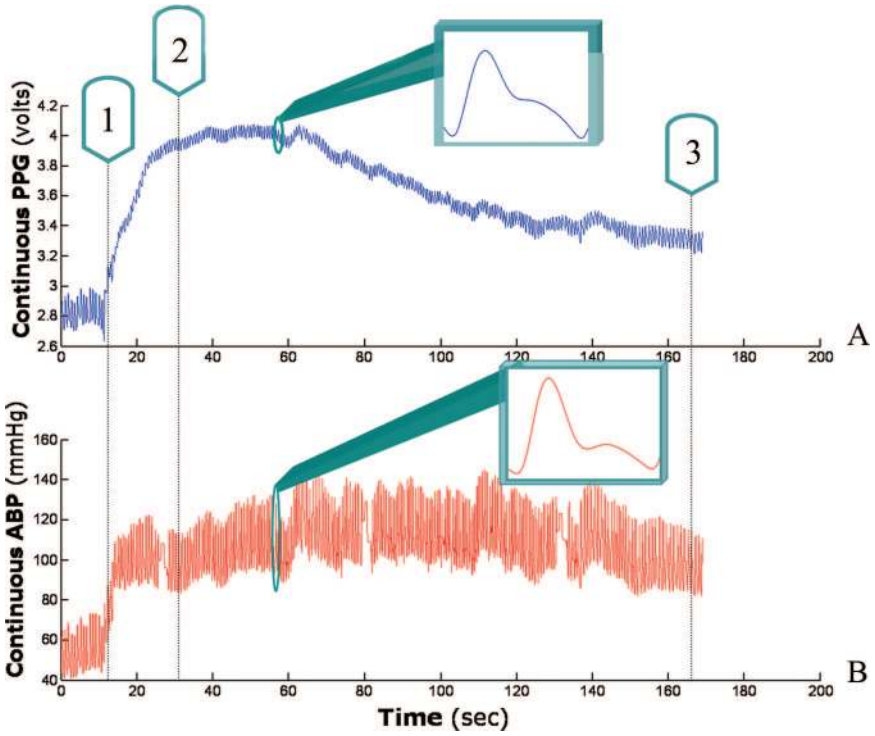

Fig. 2. Photoplethysmogram time series (PPG; *A*) and arterial blood pressure time series (ABP; *B*), measured in an ipsilateral hand, using a laboratory prototype photoplethysmography sensor and the Finapres (Finapres Medical Systems, Amsterdam, The Netherlands), respectively. In this representation, several minutes of waveforms are compressed into a single image (specific waveform morphologies are illustrated in the call-outs). Before 1 = baseline. 1: Over 20 s, the subject lowers his hand, raising the local blood pressure. 2: The photoplethysmogram indicates that the hand has filled with more blood (higher waveform baseline) and the blood vessels have grown less compliant as a result of the increase in blood pressure (decreased amplitude of the photoplethysmogram, while the blood pressure's amplitude is unchanged). 3: The hand's vascularity returns toward baseline even though arterial blood pressure remains elevated, due to autoregulation. The data above were collected in our laboratory with institutional human use committee approval and subject consent.

hemolyzed erythrocytes are reflective and can act as little mirrors.[20] When a reflectance sensor is placed directly over a large superficial artery, the photodetector light intensity demonstrates a strong positive correlation with ultrasonic diameter measurements.[11] Yet in the majority of *in vivo* reflectance-mode applications, the relation between blood volume and the photoplethysmogram is similar to transmission modes[1]: Light from the diode enters the tissue, is reflected by deeper structures, and "backlights" superficial blood vessels. Then, as superficial blood vessels fill with more blood, they absorb more light returning from the deeper tissues, and photodetector light intensity diminishes. Any increase in directly reflected light is negligible compared with the absorption of light returning from the deeper tissues.

Note that reflectance-mode probes are often adhered to the patient and may not apply enough pressure to collapse the low-pressure venous system, so venous oscillations can be more significant than in transmission-mode photoplethysmography.[27,28] Oscillations in low-pressure vasculature are, in part, due to respiratory effort, so reflectance mode has been used to extract respiratory rate and volume data from the photoplethysmogram.[29,30] A finger probe, *i.e.*, transmission-mode photoplethysmography, can compress the tissue with a variable range of pressures, whereas a reflectance sensor that is adhered to the skin can avoid the major confounding effects of probe pressure on the photoplethysmogram (discussed in the next section). On the other hand, minimal skin pressure applied by the probe often means a worse signal-to-noise ratio. Overall, there is insufficient experience to judge when reflectance or transmission-mode photoplethysmography is preferable for the hemodynamic applications that are reviewed in the next section.

Hemodynamic Monitoring Applications of Photoplethysmography

Since the 1930s, decades of physiology research have been conducted using the baseline level of the photoplethysmogram (often referred to as the *direct current* [DC] component) as a relative, nonquantitative index of skin vascularity (*e.g.*, local hyperemia or hypoemia) caused by perturbations in temperature, metabolic state, drug effects, and central or local regulatory mechanisms; this extensive body of literature has been previously reviewed.[1,6] In practice, the photoplethysmogram baseline is dictated by the interplay of physiologic mechanisms. Figure 2 demonstrates a step increase in arterial pressure, which engorges a finger with blood (the baseline of the photoplethysmogram rises). Note that there is a subsequent downward drift in the baseline, or DC level, reflecting the tissue's autoregulatory compensation to the rapid increase in volume.

Oscillations in the Baseline of the Photoplethysmogram

It is a misnomer to use the term *DC* in reference to the baseline of the photoplethysmogram; the baseline is not steady, but displays low-frequency oscillations due to changes in capillary density (*e.g.*, due to episodic sym-

pathetic outflow[23,31–34] and local autoregulation) and venous volume fluctuations (*e.g.*, due to respiration-induced fluctuations in central venous pressure). Baseline oscillations in a fingertip photoplethysmogram have been reported distal to an arterial tourniquet; the authors suggest this may represent sympathetically mediated shifting of blood between different compartments of the peripheral microcirculation.[35] While oscillations in the baseline of the photoplethysmogram are technically part of the *alternating current* (AC) component, most medical literature uses the AC specifically in reference to pulsations in the photoplethysmogram generated by individual heart beats, not oscillations in the baseline.

The baseline level of the photoplethysmogram is not displayed by most commercial pulse oximeters. In fact, the photoplethysmogram is highly electronically processed by most nonresearch pulse oximeters to remove these baseline vacillations and, in general, to reduce signal distortions due to patient motion and yield a photoplethysmogram that appears "cleaner." There is no singular method for removing oscillations in the DC baseline of the photoplethysmogram, and the specific algorithm used by a device can dramatically alter the waveform morphology.[36] The processing algorithms vary between manufacturers, and their precise methods are often proprietary. Most commercial monitors also "autoscale" the photoplethysmogram so that the amplitude of the signal is adjusted (increased or decreased) to fit neatly in the display window. When not properly accounted for by the instrumentation, changes in ambient light can also be a source of error in analysis of the DC-level baseline (*e.g.*, if an instrumented hand moves away from an overhead light, less light reaches the photodetector so it may appear as if the digit had become hyperemic). In a cautionary example of how postprocessing must be borne in mind when examining a monitor's photoplethysmogram, there is a case report of a patient who experienced cardiac arrest while an undisrupted photoplethysmogram was displayed by the bedside monitor. The user manual for the Masimo SatShare tool (Masimo Corporation, Irvine, CA) expressly warns that the photoplethysmogram exported to the bedside monitor is simulated and not physiologic, but in this reported case, the clinicians were unaware of that proviso.[37]

Note that changes in the DC baseline impact the amplitude of the AC pulsatile waveform. Each AC pulse of blood causes a fractional loss of light (in accordance with the Beer-Lambert law), at most a few percent of the total intensity. When there is less baseline light, the fractional loss yields a low-amplitude AC signal. When there is more baseline light, the same fractional loss produces a higher-amplitude AC signal. Hence, an AC amplitude can increase when a tissue's baseline optic density is reduced, *e.g.*, hypoemia, or if the incident light is increased, *e.g.*, turning on an overhead light.

The Photoplethysmogram *versus* Arterial Blood Pressure

The pulsatile AC signal of the photoplethysmogram is similar in morphology to an ABP waveform, so it is intuitive that they are related and to seek information about ABP from a readily available photoplethysmogram. First, we consider the relation between the ABP and basic (*i.e.*, not photo-) plethysmography (fig. 1). Time plots of arterial diameter share a similar shape with ABP plots, although the typical diameter change is only 1–5% whereas the pressure change is on the order of 50%.[38] Recall that volume will be proportional to the square of a vessel's radius.

There are two major complications to the arterial pressure–volume relation. First, arterial volume is determined by the balance of internal blood pressure and external pressure, not by blood pressure alone. Blood vessels grow ever less compliant at extremes of pressure (*e.g.*, nonlinear compliance), so plotting vascular transmural pressure *versus* volume yields a sigmoid-shaped curve.[39,40] Although the photoplethysmogram is not a true plethysmogram, Ando *et al.*[41] reported that the AC signal of the photoplethysmogram *versus* arterial transmural pressure yields a similar sigmoid-shaped curve. Our group has been able to replicate similar curves using a plethysmogram measured over the digital artery, after signal processing to remove fluctuations in the DC baseline in a photoplethysmogram (fig. 3).[42] In more distal measurement locations, the pressure–volume relation of smaller vessels dictates this relation. Note that a photoplethysmogram will be altered dramatically (both in amplitude and shape) when the pressure applied by a probe is altered.[43] This is intuitive when one considers the sigmoid curve, and appreciates that it is the transmural pressure (blood pressure minus external pressure) that determines vessels' volumes (fig. 3).

Second, as shown in figure 4, on a beat-to-beat basis, it is more accurate to think of pressure–volume loops rather than static curves, because of hysteresis.[27] The loops occur because of dynamic compliance and stress–relaxation, which are intrinsic properties of arteries and veins. Dynamic compliance means that vessels are stiffer when their pressure changes quickly (*e.g.*, intrabeat) and more compliant when their pressure changes slowly (*e.g.*, interbeat), as illustrated in figure 4. Therefore, a photoplethysmogram can appear dampened relative to the ABP, lacking in higher-frequency waveform features.[44] Electronic processing of the photoplethysmogram also can create an artifactual appearance of hysteresis. The specific slope of a photoplethysmogram–*versus*–transmural pressure curve is a function of the mechanical properties of the pulsating vessels and is sensitive to the subject's physiologic state.[27] It can take a blood vessel minutes to alter its mechanical properties in response to physiologic stimuli.[45]

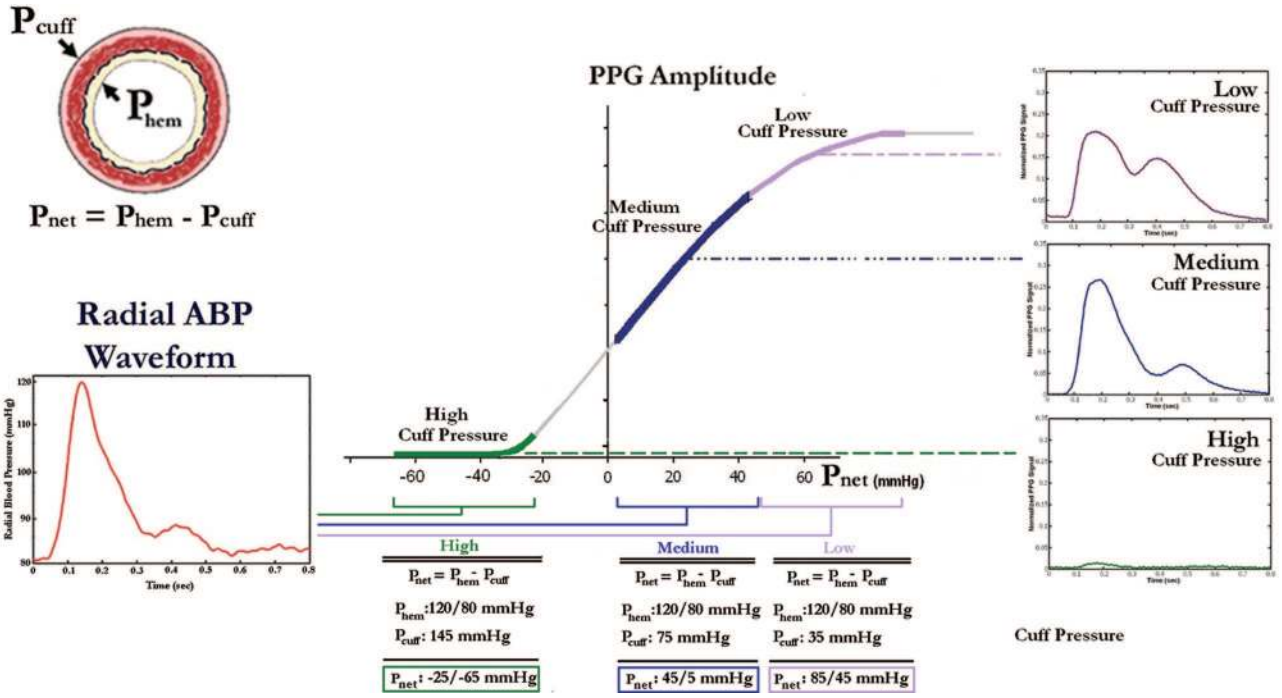

Fig. 3. A sigmoid-shaped curve, such as the one above, captures some of the underlying relation between arterial blood pressure (ABP) and the photoplethysmogram (PPG). Note the following: (1) The abscissa is the transmural arterial wall pressure (P_{net}), the net difference between arterial pressure (P_{hem}) and any externally applied cuff pressure (P_{cuff}). (2) The curve is most compliant (maximum slope) when transmural pressure is zero. (3) There are nonlinear portions at the extremes of the curve: It is increasingly difficult to further expand or collapse the vessel after it reaches certain limits. (4) The amplitude and shape of the photoplethysmogram can be changed by different external cuff or probe pressures, illustrated above: Given a relatively consistent arterial blood pressure waveform, the resultant photoplethysmogram (a) is collapsed, (b) is similar to the blood pressure waveform, or (c) has its peaks compressed, when the external probe/cuff pressure is (a) high, (b) medium, and (c) low, respectively. The data above were collected in our laboratory with institutional human use committee approval and subject consent. The photoplethysmogram was recorded overlying a digital artery.

Computational devices to estimate ABP from the photoplethysmogram have included linear transfer functions and neural networks. Millasseau *et al.* [46] showed that the shape (but not absolute value) of ABP can be estimated from the photoplethysmogram using a population-averaged transfer function. Allen and Murray[47] showed that, using a neural network that was first individually calibrated to each subject, the ABP could be subsequently estimated from the photoplethysmogram during controlled laboratory conditions. In the 1980s, Yamakoshi *et*

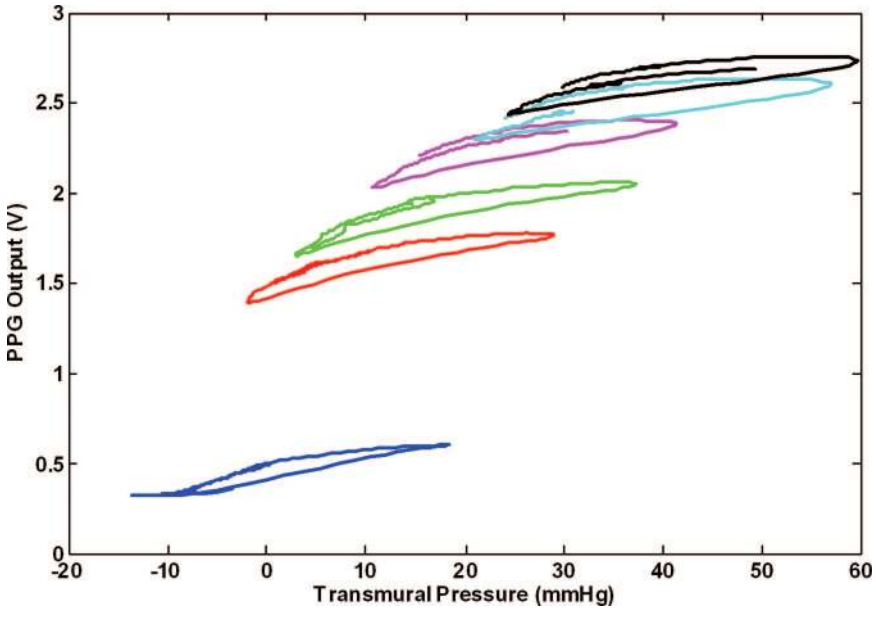

Fig. 4. Illustration of loops of arterial pressure (transmural) *versus* the photoplethysmogram (PPG). Note that the vessels are more compliant (*i.e.*, Δvolume/Δpressure) interbeat than intrabeat. This is explained by dynamic compliance, a property of blood vessels. Also note that physiologic fluctuations in the baseline of the waveform must be removed by some algorithm to reproduce this image.[32] The interbeat pressure–volume loops reveal a portion of the sigmoid curve illustrated in figure 3. The data above were collected in our laboratory with institutional human use committee approval and subject consent. The photoplethysmogram was recorded overlying a digital artery. V = photodetector voltage, which is a function of light intensity.

al.[48] used photoplethysmography in a variation of conventional oscillometry that attached to the finger base.

The Volume Clamp Method

The Finapres/Portapres/Finometer family of devices (Finapres Medical Systems, Amsterdam, The Netherlands) enables noninvasive measurement of the ABP waveform from a finger using an inflatable cuff in conjunction with photoplethysmography. In numerous instances, published works may refer to this measurement modality as "photoplethysmography" (*e.g.*, references 49–51) although such usage is imprecise, and it can leave the incorrect impression that the photoplethysmogram and the ABP signal are interchangeable. The Finapres uses the volume clamp method of Penaz, which is based on the following insight: If a photoplethysmogram is not changing, neither is the arterial transmural pressure, and *vice versa*. Using an extremely rapid servo system with a finger cuff actuator, the Finapres adjusts the pressure in a finger cuff to keep a reference photoplethysmogram flat throughout systole and diastole; the method is thus known as the *volume clamp* because the finger's blood volume in held constant. The waveform of whatever cuff pressure is necessary to keep the photoplethysmogram flat must be equal to and opposite the digital arterial ABP. The method is attractive in that it offers a noninvasive, continuous ABP digital artery measurement, although historically it tends to underestimate blood pressures.[52] Moreover, differences in systolic blood pressure (SBP) measured in the finger *versus* brachial SBP are a function of arterial compliance, changing with age.[53] A newer model seems to have improved accuracy that is comparable to other noninvasive blood pressure devices,[54] although there remain questions about its performance in subpopulations (*e.g.*, pregnant patients[55]) and the validity of its reliance on a generalized transfer function for all patients and physiologic states (*e.g.*, references 56 and 57).

The Perfusion Index and Other Correlates of Hemodynamic State

The new Masimo SET pulse oximeter (Masimo Corporation, Irvine, CA) reports a perfusion index, the ratio of the pulsatile amplitude of a photoplethysmogram to its DC component. Early reports suggest that the perfusion index is sensitive to proximal sympathectomy,[58] proximal arterial clamping,[59] and neonatal left heart obstruction.[60] Other metrics from a photoplethysmogram that have been recently investigated are related to beat-to-beat waveform variability of either peak levels or amplitude, which are nonspecific metrics analogous to ABP pulsus paradoxus. Changes in waveform variability metrics have been significantly associated with hypotension (for systolic variation and δ-down: $r = 0.6$ correlation with ΔSBP[61]), respiratory volume (for a novel oscillation metric: $r = 0.89$ correlation with breath volume[30]), wedge pressure (for δ-down: $r = -0.6$ correlation with wedge pressure[62]), and hypovolemia (systolic variation of $17 \pm 12_{SD}$% at baseline *vs.* systolic variation of $32 \pm 12_{SD}$% after loss of 10% blood volume[63]). The Masimo SET pulse oximeter reports perfusion index variability, which will presumably show similar correlations.

There are a number of other waveform features that correlate with central hemodynamic parameters. In the operating room, a measure of the photoplethysmogram's systolic width correlated with mean arterial pressure ($r = 0.80$).[64] In a cardiac catheterization suite, the "maximum decreasing systolic slope" correlated with changes in peripheral vascular resistance ($r = 0.66$).[65] Features from the second derivative of the photoplethysmogram have been correlated with vascular compliance.[66–68]

Correlations and Covariates

That features of a photoplethysmogram are correlates of important hemodynamic parameters is not surprising. What is crucial to appreciate is how a multitude of effects can confound any of the preceding correlations when not carefully controlled. We note that the majority of photoplethysmography investigations to date report significant correlation statistics but do not report test characteristics (*e.g.*, sensitivity and specificity). Novel photoplethysmography applications may be most useful when one clear-cut factor is changing at a time, *e.g.*, ventilation or circulatory state or anesthetic state. For example, it has been observed that the pulsatile amplitude of a photoplethysmogram, which is a major determinant of the perfusion index, may serve as a measure of depth of anesthesia, with higher amplitude indicating deeper anesthesia.[69] But in practice, an increase in amplitude could be caused by other physiologic or external phenomena (table 1). To apply photoplethysmogram waveform analysis in a reliable and reproducible manner (*i.e.*, without dangerous false positives and false negatives), it is important to consider all potential confounding effects. Was the probe's skin pressure kept constant? Exactly how were baseline oscillations mathematically removed (as noted above, the photoplethysmogram displayed is a function of the manufacturer's postprocessing algorithms)? Was the height of the sensor (relative to the subject's heart) held constant? Did medication or temperature effects alter the local tissue vascularity? Pending further contributions to the literature, notable changes in the photoplethysmogram should make a prudent clinician reassess the patient's condition to seek an explanation. However, photoplethysmogram changes will likely be nonspecific, and they are not necessarily sensitive enough to substitute for standard diagnostic practices.

Table 1. Example of Ambiguities in the Photoplethysmogram: Multiple Processes Can Increase the Absolute Signal Amplitude

↑ Arterial pulse pressure (*e.g.*, in the setting of bradycardia)
Δ Vascular state (*e.g.*, exercise or local warming) ►► ↑ vascular compliance
↑* Height of the hand (relative to the heart) ►► ↓ hand transmural pressures ►► ↑ compliance
↑* Cuff/probe local pressure ►► ↓ transmural pressures in hand ►► ↑ compliance
↓* Central mean arterial pressure ►► ↓ transmural pressures in hand ►► ↑ compliance
↓ Volume pulse (actual) ►► manufacturer's postprocessing/autoscaling
↓ Optic density in the tissue (*e.g.*, reduction–oxidation of chromophores or ↓ capillary density)†
↑ Ambient light†

* If the cuff/probe pressure is *greater* than vascular pressures, then (1) lowering the hand, (2) reducing cuff/probe pressure, or (3) increasing mean arterial pressure would increase vascular compliance and increase amplitude of the photoplethysmogram (fig. 3). † The Beer-Lambert law suggests that an absorber (*i.e.*, pulse of blood) causes a fractional loss in light intensity, so the greater the light intensity passing through an absorber, the greater will be the loss of light in absolute terms. Pulsatile amplitude (the absolute difference between systolic and diastolic light transmission) increases if the incident light is increased (*i.e.*, more light initially) or if the tissue's optic density is reduced (*i.e.*, less light lost passing through nonpulsatile tissues).

Δ = change; ↑ = increase; ↓ = decrease; ►► = cause.

Indication of Pulsatile Perfusion

The simplest photoplethysmography application is to test for the presence or absence of measurable perfusion (*e.g.*, a measurable pulsatile photoplethysmogram). One case series explored photoplethysmography as an indicator of efficacious chest compressions during cardiac arrest, with mixed success.[70] Chest compressions can lead to a deceptively pulsatile photoplethysmogram (*i.e.*, related to jolting movements, not vascular pulsation). It has been suggested that with placement of the photoplethysmography probe in an isolated location, *i.e.*, a finger, and with careful inspection of the waveform, *i.e.*, visualization of a dicrotic notch, the photoplethysmogram can be helpful during cardiopulmonary resuscitation.[71] In a related application, photoplethysmography was used in a small case series as a continuous indicator of graft viability after revascularization.[72] Note that a pulsatile photoplethysmogram can be misleading in the setting of venous obstruction[73]: The upstream arteries may still pulsate (hence the photoplethysmogram appears pulsatile) without any net flow through the tissues.

Loss of a pulsatile photoplethysmogram distal to a cuff being inflated indicates when the cuff pressure is close to a subject's SBP. The use of photoplethysmography to determine when distal flow is cut off by the cuff is comparable to other indicators that pulsatile flow has ceased, including direct arterial cannulation ($r = 0.99$),[74] Doppler ultrasound ($r = 0.99$),[75] and manual palpation ($r = 0.97$).[76] In some studies, actual SBP was slightly higher than what was estimated,[74,75] although one investigation found that photoplethysmography-based SBP measurement was superior to standard cuff oscillometry for small pediatric patients.[77] Note that hypotension (*e.g.*, SBP <60 mmHg[78]), peripheral vasoconstriction (*e.g.*, pressor therapy[78] or cold[79]), or vascular lesions may reduce or eliminate any measurable pulsatile photoplethysmogram in distal and/or cutaneous beds and confound this method of measuring SBP.

Measuring Pulse Transit Time

As an indicator of pulsatile flow, photoplethysmography can also be used to measure the pulse transit time (PTT) between an upstream arterial pressure pulse and a distal peripheral pulse. PTT is a function of pulse wave velocity, which is a function of blood pressure. In some conditions, pulse wave velocity and blood pressure are highly correlated (*e.g.*, $r = 0.97$).[80] However, pulse wave velocity is more accurately a function of arterial compliance, which is certainly a function of blood pressure but also of the subject's arterial properties and physiologic state. Also, to compute PTT, a proximal and a distal measurement are necessary. Options for the proximal signal include the sound of the mitral valve, a proximal photoplethysmogram or ABP signal, or an electrocardiogram, although the electrocardiogram is not a reliable indicator of mechanical systole.[81] Such issues have been reviewed, with recommendations available for PTT/pulse wave velocity applications.[82,83] In general, PTT is not an acceptable alternative to standard noninvasive blood pressure measurements, although the capability to continuously monitor trends in arterial compliance is valuable for physiologic research.

Measuring Heart Rate

A pulsatile photoplethysmogram of course reveals the heart rate (HR) and could be used to monitor HR variability. General Electric's new IntelliRate algorithm (GE Healthcare, Little Chalfont, United Kingdom) uses the photoplethysmogram as an ancillary to electrocardiography, to reduce false electrocardiographic alarms related to nonperfusing arrhythmias. But as an HR-monitoring modality, photoplethysmography is unable to distinguish between electrically narrow-complex and wide-complex beats, and electrical–mechanical disassociation will cause a discrepancy between a photoplethysmographic HR and electrocardiographic HR. There is insufficient evidence to warrant the use of photoplethysmography for primary HR monitoring, because the shape of a normal pulse may be less morphologically distinct than the QRS complex of an electrocardiogram, particularly in the setting of motion artifact.[84]

Conclusion

Recent evidence suggests that photoplethysmography offers a fruitful avenue for new technologic develop-

ments in noninvasive circulatory monitoring. The challenge is the many covariates that affect the appearance of the photoplethysmogram. In the future, novel bedside devices and alarm algorithms might exploit the richness of the photoplethysmogram, although these may demand some compensation for ambiguities in the signal.

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