Remote Photoplethysmography (rPPG)

Biophysical Foundations and Applications for Non-Contact Vital Signs Monitoring

RESEARCH REPORT

Author
Fabrice De Oliveira, Head of Research, i-Virtual

version 1.0
January 20, 2025

i-Virtual.ai

1. Introduction

Remote Photoplethysmography (rPPG) is a cutting-edge technology that enables the non-contact measurement of physiological parameters (heart rate (HR) and blood pressure (BP)), using a standard RGB camera. By analyzing subtle changes in skin color caused by blood volume variations, rPPG extends the principles of photoplethysmography (PPG) to a remote sensing context. This innovative approach eliminates the need for physical contact, making it ideal for applications across diverse industries, including telemedicine, fitness monitoring, wellness, insurance and other applications requiring non-invasive physiological measurements.

The biophysical basis of rPPG relies on the optical properties of hemoglobin, the oxygen-carrying molecule in blood, which absorbs light in specific ways. As blood circulates and volume fluctuates, it alters how light reflects from the skin, allowing rPPG to detect these changes and derive vital health information.

However, while heart rate and blood pressure measurements using rPPG are scientifically supported, claims regarding the ability to monitor other biomarkers like blood glucose and other blood components have not been scientifically validated. Despite its potential, the technology also faces challenges such as motion artifacts, lighting variability, and skin tone diversity, requiring robust signal processing techniques to ensure accurate measurements.

This white paper explores the foundational principles of rPPG, offering a detailed examination of its signal acquisition and processing workflows, and discusses its applications and limitations. Through this comprehensive overview, we aim to highlight the transformative potential of rPPG in unlocking new possibilities across diverse industries and address the unproven claims of its ability to measure certain complex biomarkers.

2. rPPG Biophysical Principles

Optical interaction of ambient light with the skin

rPPG works by capturing how light interacts with skin layers, specifically in terms of absorption and scattering. This section explains how light absorbed by blood, particularly hemoglobin, creates a detectable signal:

- **Light absorption**
  - Hemoglobin, the primary oxygen-carrying molecule in blood, absorbs light differently depending on whether it is in its oxygenated or deoxygenated states.
  - Optical light is typically composed of green, blue and red spectrum. Green light (~530 nm) is particularly effective for detecting blood volume changes, as hemoglobin strongly absorbs it. These variations in blood volume due to the cardiac cycle are key to measuring heart rate.

- **Light scattering and reflection**
  - Once light penetrates the skin, it interacts with structures such as the epidermis, dermis, and subcutaneous layers. These interactions scatter light in multiple directions.
  - The most significant scattering occurs in the dermis, where capillaries and blood vessels reside, making it the primary location for detecting blood flow and volume changes.
  - As blood volume increases during the cardiac blood pulse, more light is absorbed and less is reflected to the surface. This interaction forms the basis of the rPPG signal.

How does light help us measure blood flow?

Imagine if your camera could see tiny changes in your skin color every time your heart beats.

That’s exactly what remote photoplethysmography (rPPG) does: **it uses light to read your blood flow**.

When light shines on the skin, some of it is absorbed, and some is reflected back. These subtle changes in reflection are tied to blood flow under the skin:

Blood absorption

- Blood absorbs more light, especially in the green wavelength, during the heart's contraction phase. This makes green light ideal for tracking blood flow.

Skin reflection

- The remaining light is reflected back to the surface, changing with each heartbeat and providing insight into the heart's rhythm and blood volume fluctuations.

Our skin functions as a natural filter. The top layer reflects some light, while deeper layers scatter it. The middle layer, where blood vessels are located, provides the most useful signals. Although these signals are invisible to the naked eye, a camera can detect them and convert them into useful information.

This is the basis of rPPG, a non-invasive method of measuring heart rate and other vital signs without direct skin contact.

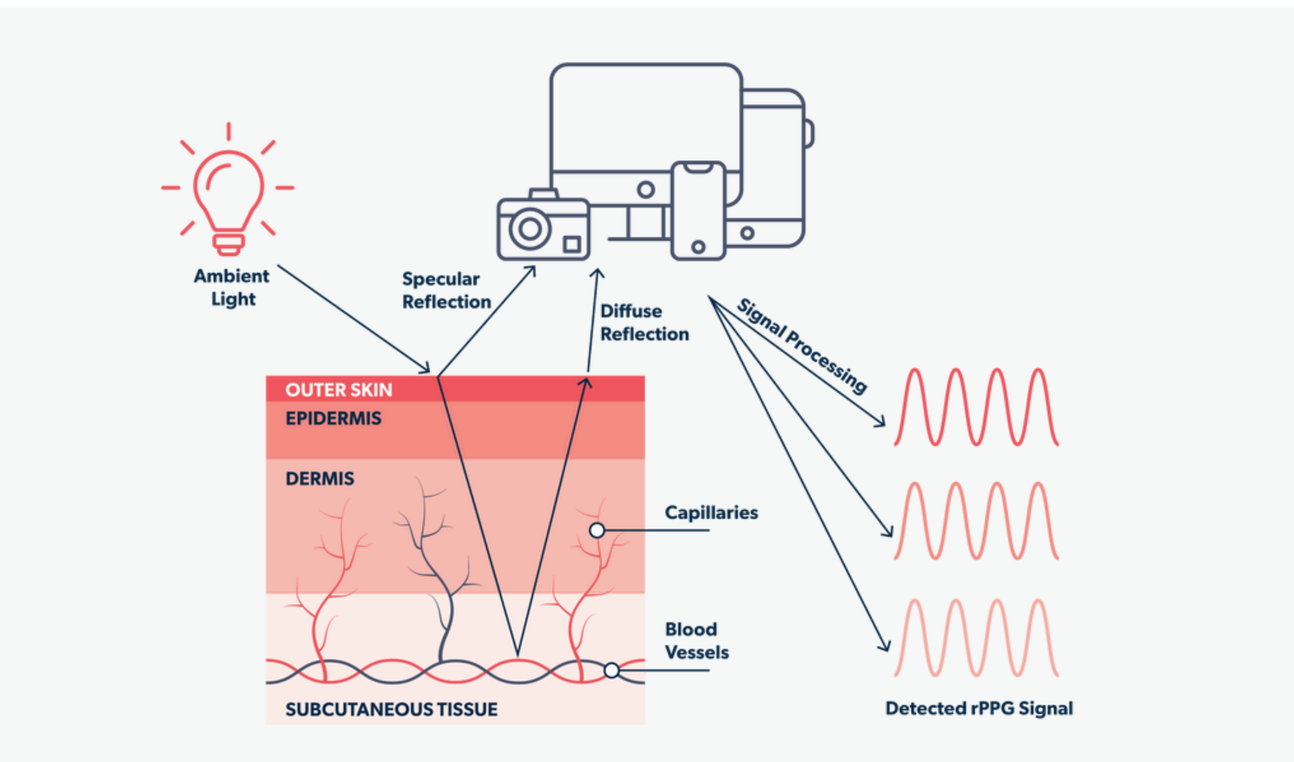

Figure 1 - rPPG principle and light interaction with skin layers

3. Blood Volume Pulse (BVP)

The primary rPPG signal, known as the blood volume pulse (BVP), reflects periodic changes in blood volume associated with the heartbeat. These variations, observed through skin color changes, are the foundation for heart rate and vascular health measurements.

Phases of the cardiac cycle

- Systole: During heart contraction, blood is pumped into the arteries, increasing blood volume and reducing reflected green light due to greater absorption.
- Diastole: As the heart relaxes, blood volume decreases, and more light is reflected to the surface.

Signal characteristics

The rPPG waveform has two main components:

- AC component: Corresponding to the pulsatile blood flow, it provides information about heart rate and vascular function.
- DC component: Reflects baseline skin reflectance influenced by tissue structure, pigmentation, and ambient lighting.

Signal features

- The BVP frequency corresponds to the heart rate, typically ranging from 0.8 Hz to 1.2 Hz in healthy adults.
- The signal's amplitude and periodicity are influenced by physiological factors such as vascular health and stress levels.

What happens during a heartbeat?

Every time your heart beats, it pumps blood through your body, creating a pulse. This pulse causes the blood volume in small vessels under your skin to rise and fall.

- When the heart pushes blood out (systole), the blood volume increases, and more light is absorbed by the skin.
- When the heart relaxes (diastole), the blood volume decreases, and less light is absorbed.

This pattern repeats with every heartbeat, creating a wave-like signal called the blood volume pulse (BVP).

4. Signal Acquisition

The rPPG signal is captured using a standard RGB camera. The process is as follows:

1. **Video recording**: A video of the subject's face is captured under stable lighting conditions.
2. **Detecting color changes**: The camera records subtle skin color variations due to blood flow, mainly focusing on the green channel, which is most sensitive to blood absorption.
3. **Cleaning the data**: The raw signal is often noisy, so advanced processing techniques like band-pass filtering and decomposition are used to isolate the relevant heart rate signal.
4. **Extracting insights**: Cleaned signals from the video are analyzed to derive health indicators like heart rate and respiratory rate.

How it works

The visualization below demonstrates how a simple camera can be used to extract complex physiological signals using light and advanced signal processing techniques. A camera records a person's face and splits the video into red, green, and blue light. Tiny skin color changes caused by blood flow are captured, with the green channel being most sensitive. The signals are cleaned to remove noise, revealing heart rate, breathing rate, and other health insights.

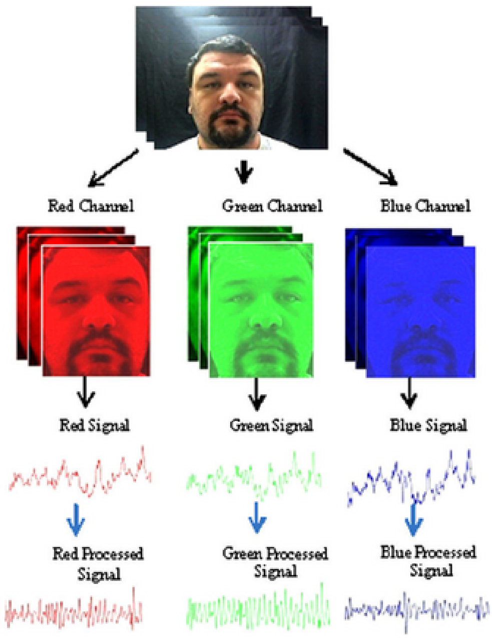

Figure 2 - rPPG extraction in red, green, and blue images from a selfie

5. Regions of Interest

To get the clearest and most accurate readings , certain areas are better for capturing signals. These regions, known as regions of interest (ROI), are chosen because they provide the best data for tracking heart rate and blood flow.

Where do we measure?
When it comes to measuring signals, some parts of your body are better than others:

- The **face**, particularly the forehead, cheeks, and nasal bridge, is commonly used due to its high vascular density and minimal interference from hair or thick skin (cf. Figure 3).
- The **hands**, especially the palm and fingertips, can also provide reliable signals.

These regions are chosen because they are easy to monitor with a camera and the signals they provide are clear and stable.

For example, the skin on your face and hands is thinner, making it easier to detect tiny changes in blood flow.

How do we improve the signal?
Sometimes, external factors like lighting or movement can affect the signal quality. Selecting areas with stable lighting and minimal movement enhances signal clarity. Advanced techniques such as face tracking and dynamic ROI adjustment improve the robustness of measurements.

Why specific regions of the face?
To get the best measurements, we divide the face into different areas or regions of interest (ROIs), such as the forehead, nose, cheeks, mouth, and chin. Each ROI generates a unique rPPG signal, shown on the left side of the image as color-coded waveforms (cf. Figure 4).

- Forehead & cheeks: These areas give the strongest and clearest signals. They have lots of blood vessels, and the skin is stable, which helps capture accurate data.
- Nose bridge (nasion): This area gives a decent signal, but the bone structure underneath can sometimes reduce accuracy.
- Mouth & chin: These areas often show more noise, as movement (like talking or smiling) can interfere with the signal.

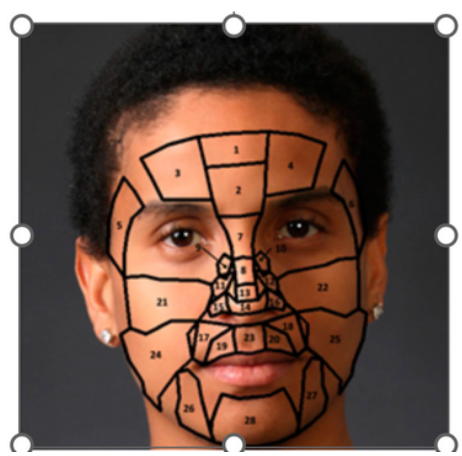

Figure 3 - Regions of interest

Why use multiple areas of the face?
The face is full of subtle signals. By combining data from different areas, the system can provide more reliable results. For example, if the signal from your mouth is unclear because you are talking, the system can still rely on signals from the forehead or cheeks. These areas show clearer waves because they have more blood flow and don't move as much.

Why is this important?
Using multiple regions of the face increases the accuracy and reliability of the measurements. Even if you are moving or the lighting is not perfect, the system can pull from different areas of your face to get the best possible reading. It's like using all the tools in your toolbox to make sure the job gets done right!

Figure 4 illustrates the extraction of rPPG signals from various regions of the face, demonstrating how different areas contribute to the overall signal quality.

6. Challenges and Limitations

rPPG can effectively measure vital signs like heart rate and heart rate variability, but it faces challenges when extended to more complex biomarkers like blood pressure, blood oxygen, blood glucose or other blood components such as cholesterol or proteins. Although there are claims in the industry that rPPG technology can monitor other physiological markers, they remain unproven and have been met with skepticism.

Key challenges and current limitations include

Signal quality and robustness

- rPPG signals can be sensitive to environmental disturbances such as lighting variability, head movements, and facial occlusions. Advanced signal processing methods, dynamic ROI adjustments, and deep learning-based noise reduction algorithms represent promising areas for future development.

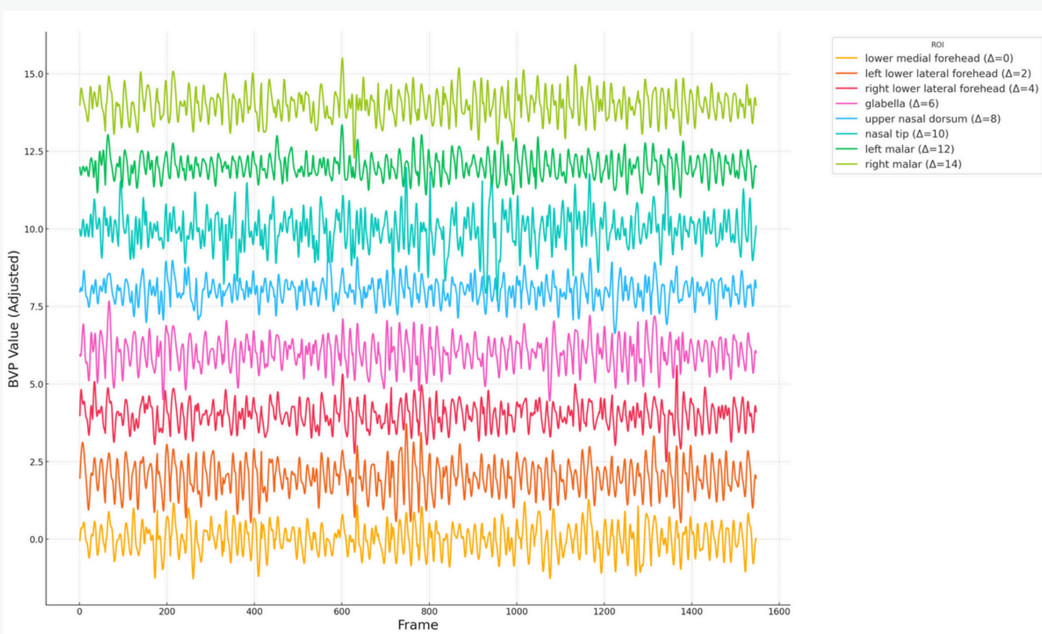

Figure 4 - rPPG signal quality per ROI

Standardized validation protocols

- A clear gap exists in standardized validation protocols specifically for rPPG-based predictions of biomarkers like BP. Establishing robust validation frameworks and guidelines will significantly enhance the credibility and clinical acceptance of rPPG solutions.

Temporal correlation and heart rhythm variability

- Current rPPG methods have difficulty accurately tracking signals with irregular heart rhythms, such as atrial fibrillation. Improvements in signal synchronization techniques and the use of deep learning algorithms specialized for irregular rhythms are promising areas of ongoing research.

Data diversity and generalizability

- Many existing datasets lack demographic and physiological diversity. Increasing dataset diversity, encompassing a broader demographic range and a wider spectrum of health conditions, is critical for enhancing the generalizability and real-world applicability of rPPG solutions.

Complex biomarkers measurement

- Biomarkers such as blood glucose, cholesterol, and protein concentrations pose challenges due to their subtle and overlapping optical signatures. Current evidence indicates that accurate non-invasive measurement of these biomarkers with rPPG alone remains limited.

Despite these challenges, significant opportunities lie ahead

Technological advances

- Rapid progress in sensor technology, multispectral imaging, and advanced optical sensors may soon improve the detection and measurement of subtle physiological signals.

AI and machine learning advances

- Machine learning, particularly deep neural networks, promises substantial improvements in signal quality enhancement, noise reduction, and feature extraction, enabling more accurate and robust physiological measurements.

Multi-modal approaches

- Combining rPPG with complementary technologies like thermal imaging, hyper-spectral imaging, or advanced infrared sensors could dramatically enhance measurement accuracy and expand the range of detectable biomarkers.

7. Conclusion

This report has explored the biophysical principles underpinning rPPG, including its reliance on light absorption and scattering within the skin's layers, the critical role of hemoglobin in signal generation, and the decomposition of color channels for extracting pulsatile signals.

The advantages of rPPG, such as its accessibility using standard RGB cameras, non-invasiveness, and potential for multimodal health insights, make it a valuable tool for a wide range of applications. From telemedicine to fitness monitoring and even biometric authentication, rPPG offers a versatile platform for health and wellness technologies. However, challenges such as motion artifacts, lighting variability, and skin tone diversity must be addressed through advancements in signal processing and AI adaptive algorithms.

While current limitations are significant, ongoing research and rapid technological advancements indicate a bright future for rPPG. With continued innovation, robust validation, and multi-modal integration, rPPG is expected to extend beyond heart rate and blood pressure to reliably measure a broader range of physiological markers, transforming remote vital sign monitoring. ●

i-Virtual

References

[1] Man, P.-K.; Cheung, K.-L.; Sangsiri, N.; Shek, W.J.; Wong, K.-L.; Chin, J.-W.; Chan, T.-T.; So, R.H.-Y. Blood Pressure Measurement: From Cuff-Based to Contactless Monitoring. Healthcare 2022, 10, 2113. https://doi.org/10.3390/healthcare10102113
[2] B. D. Holton, K. Mannapperuma, P. J. Lesniewski and J. C Thomas, 2013, Signal recovery in imaging photoplethysmography, IOP Publishing, volume 34, number 11,pages 1499, DOI:10.1088/0967-3334/34/11/1499,
[3] Li, S., Elgendi, M. & Menon, C. Optimal facial regions for remote heart rate measurement during physical and cognitive activities. npj Cardiovasc Health 1, 33 (2024). DOI:10.1038/s44325-024-00033-7