Non-invasive health monitoring is now a reality thanks to recent developments in wearable sensors.

In addition to the fast-paced technological advance of sensors, low-cost and low-energy CPUs with large memories can process complex algorithms in the small footprints of wearable devices. The latest trend in the market is to merge two distinctly different sensing modalities in one chip to further miniaturise the function.

Accommodating two sensors in a single chip brings several advantages, with reductions in footprint, power and circuit board layout effort. It also improves sensor accuracy by synchronising sensor sampling and minimising sampling time jitter.

Finally, it increases battery life by offloading control tasks from the master CPU.

What is heart failure?
Cardiac output is measured by the total volume of blood pumped out of the left ventricle over a given time span. The blood volume per cardiac contraction is called the stroke volume.

The cardiac output is obtained by multiplying the stroke volume with the number of heart beats per minute (BPM).

When heart failure occurs, the heart pumps out blood in much lower volumes than in a healthy heart. There are three main reasons for this: left ventricular hypertrophy, cardiac valve stenosis and left ventricular ischemia.

A two-sensor, single-chip device can be used to focus on left ventricular hypertrophy (LVH) to monitor chronic heart failure trending with electrocardiogram and photoplethysmogram/bioimpedance (ECG+PPG/BioZ) sensors in a clinical application.

Left heart failure is due to LVH, which is when the left chamber of the heart develops thick muscle and decreases the inner blood-filling volume in the left ventricle. The increased cardiac muscle mass of LVH exacerbates poor cardiac output because thick muscles have weak contracting force, resulting in lower blood pressure and triggering poor cardiac output.

The danger of heart failure is not in the poor cardiac output, however. When heart failure happens, cardiac output from the left ventricle decreases while the right ventricle keeps pumping out to the lung.

This unbalanced pressure difference in the cardiac chambers causes fluidic plasma to leak into the lung. Plasma-filled lungs decrease oxygen delivery and carbon dioxide removal.

In a patient, this manifests itself as shortness of breath. The heart also needs to receive a continuous stream of oxygenated blood. The reduction of the oxygen supply due to fluid-filled lungs often leads to cardiac ischemia, exacerbating heart failure.

Chronic heart failure monitoring
Patients with heart failure are often admitted to hospital for fluid overload. Heart failure is among the most common reasons for hospital admission in the United States. The onset of fluid overload is often difficult to self-diagnose for patients without the insights that can be provided by a medical device. Early symptoms such
as a cough, fatigue, shortness of breath during exertion, weight increase due to fluid retention, and rapid heartbeat are often ignored.

In the paper *Intrathoracic Impedance Monitoring in Patients With Heart Failure: Correlation With Fluid Status and Feasibility of Early Warning Preceding Hospitalisation,* Dr CP Lau and colleagues monitored pulmonary oedema in pacemaker patients using an intrathoracic impedance device with capabilities similar to that of a BioZ feature. The study showed that the onset of fluid accumulation can be detected about two weeks earlier by monitoring chest impedance and taking appropriate measures in the early stages of heart failure.

This can potentially prevent the condition from becoming more serious, since patients could take preventative measures such as reducing salt intake, using an extra pillow under the back during sleep to help redistribute excess body fluid, taking a diuretic, or going to a medical clinic for care.

The image below illustrates pulmonary oedema, the condition in which there is excess fluid in the lung.

**UNHEALTHY ALVEOLI**

**Fluid build-up in Alveoli, Fluid Leakage into Lungs**

**Left Lung**

This is a potential indicator of heart failure, where excess fluid accumulates in the air sacs in the lungs and makes breathing difficult.

Wearables provide one means to continuously monitor health parameters that relate to heart failure. Although wearable device manufacturers are attempting to develop devices for blood pressure or cardiac output measurement, they still face many challenges.

**Wearables to monitor chronic heart failure**

Some practical methods for heart failure monitoring via wearable devices include measurement of electromechanical delay (EMD) and monitoring of lung fluid accumulation.

EMD is the delay in the onset of cardiac muscle shortening following local electrical depolarisation, and can be on the order of tens of milliseconds. EMD is represented by the time from cardiac contraction – as indicated by R-peak in an ECG – to the maximum peak of each stroke volume (Figure 2, page 30).

A heart’s pacemaker cell sends out electrical pulses for cardiac muscle contractions; it takes time before blood pumps out of the heart to physically reach other organs in the body. This delay from pulse generation (ie. electrical) to maximum blood flow (ie. mechanical) is EMD.

As this delay increases in dyssynchronous heart failure, the heart may not pump out blood efficiently from the left ventricle, which eventually increases blood pressure in the lungs. When plasma (the liquid part of blood, without the cells) accumulates in the lung, conductivity at the cellular level increases compared to the lung when it is filled with air.

By injecting a constant DC current, a wearable device measures resistance. Injection of a constant AC current allows the device to measure reactance. From the resistance and the reactance, a wearable device can capture the overall impedance of the lung, which indicates fluid accumulation.

In addition to showing the fluid status, slow undulation of this impedance signal shows respiration. Inspiration in the lung increases impedance, while expiration decreases impedance. Using impedance sensors, it is possible to monitor the respiration rate for indications of shortness of breath as well as fluid in the lung.

Since it is in the order of tens of milliseconds, EMD can be better observed with a synchronised ECG+PPG IC. This synchronised approach would eliminate the issue of data misalignment between ECG and PPG due to different sampling rates from the respective sensors.

If two devices have different sampling rates, the samples will increasingly skew from one another. Software can compensate for the skew by selectively dropping samples, but this results in (very large) jittering. Another way to minimise the jittering issue is for the system to sample fast enough to minimise the effect of the skew with respect to the in-band signal. This, however, results in higher system power.

A typical way to synchronise two sensors is for the CPU to either use its own clock interrupt or to use the data-ready interrupt from only one of the two sensors.

When it gets the interrupt, the CPU would read both sensors. Since the two sensors continue sampling with their own time base, the skew of the two sampling clocks would cause one sample to be used twice or one sample to be skipped. In between these, there is a sampling skew of up to one sampling period (so there will be a very low-frequency artefact in the time domain signal).

**Synchronising sensors**

The start of EMD can be easily
measured by finding the maximum peak of QRS. The ending of EMD can also be measured by finding the difference from the maximum peak of QRS to the maximum of PPG between current QRS and next QRS.

While EMD is modulated naturally by the respiratory cycle in the short term, long-term increased EMD would indicate the onset of heart failure caused by body fluid overload.

The maximum of peak blood flow can be easily assessed from a PPG waveform since PPG is optically a good surrogate of blood flow in the capillary.

Comparison of EMD among normal subjects and patients with heart failure has shown that normal subjects have about 100ms, while heart failure patients have about 130ms.

Therefore, it is very important to minimise the jittering between the two sensors, especially when the wearable device samples at a slower rate to conserve battery power.

Scientific evidence indicates that early detection of the onset of heart failure can prevent the condition from becoming a full heart failure.

Early interventions include removing body fluid, improving heart-pumping function, and lowering blood pressure and heart rate.

Early detection of heart failure is now possible via less intrusive continuous monitoring of heart-pumping function, respiration rate and accumulation of fluid in the lungs.

These parameters can be easily monitored by wearing a chest BioZ patch for pulmonary oedema and a wrist-worn EMD monitor, which can alert clinicians or caregivers before symptoms worsen.

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A note on QRS

The QRS complex is a way of representing the spread of a stimulus through the ventricles as recorded in an ECG. When the initial deflection of the QRS complex is negative, it is called a Q wave. The first positive deflection in the QRS complex is called an R wave. A negative deflection following the R wave is called an S wave. (Not every QRS complex contains a Q, R and S wave.)

Figure 2: Time delay from the peak of QRS to the maximum of PPG can be used as a surrogate for cardiac electro-mechanical delay. This value is equivalent to the cardiac contractile force.

Source: www.science.com

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