Digital Signal Processing Technology in Nellcor™ OxiMax Pulse Oximeters

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Background
Reliable and accurate pulse oximetry requires the design and operation of the entire system to function together. Contributions ranging from the sensor technology, cabling and electronics, signal processing and alarm technologies, to communicating results to caregivers through local and remote displays, are all critical and interrelated (see Figure 1). Nellcor’s many years of experience in each of these individual areas has allowed us to refine and expand pulse oximetry technology into a robust tool for providing critical information to caregivers.

Each of these areas requires significant attention to detail and is deserving of a separate discussion regarding its contribution within the Nellcor OxiMax pulse oximetry system. However, in recent years much attention has focused on the internal signal processing software. This paper describes the underlying principles of the new signal processing technology used in the OxiMax N-600 pulse oximeter and other related stand-alone, handheld and OEM module products. While the processing is distinctively different from that found in Nellcor’s previous model OxiMax N-595 pulse oximeter, the OxiMax N-600 continues to deliver accurate and reliable clinical performance.

Overview of Nellcor Pulse Oximetry Signal Processing Methods
Pulse oximetry is based on a predictable relationship between a patient’s arterial blood oxygen saturation and cardiac-induced changes in the ratio of transmitted red and infrared (IR) light signals. Certain components of the monitor’s processing algorithms focus on precisely determining this relative red and infrared signal pulse amplitude. At times, weak signals and interference can obscure the cardiac-induced portions of the pulse, making an assessment of their relative sizes difficult. Nellcor and other manufacturers have developed various methods to address such challenges.

Nellcor’s signal processing methods are based on a tenet that has not changed since the earliest Nellcor™ N-100 pulse oximeter: The patient’s true arterial oxygen saturation is associated with the patient’s underlying cardiac-induced pulsatile signals. Nellcor focuses on the persistent and generally rhythmic nature of these signals, since most patients exhibit a rhythmic cardiac cycle. Nellcor’s earliest pulse oximeters targeted the cardiac portion of the signal by evaluating the beat-to-beat consistency of pulse signals.

Figure 1. Pulse oximetry comprises a system – spanning the sensor’s interaction with patient physiology, to communicating with the caregiver. Each aspect of the system contributes to the product’s accuracy and reliability.
The foundation of Nellcor's more recent OxiMax N-595 and preceding N-395 pulse oximetry technology rested on the strength of Cardiac Gated Averaging (CGA)—a method Nellcor developed for processing the optical sensor signals. CGA averages multiple waveforms synchronous with the heart rate to enhance "good" cardiac pulse signals and reduce the effects of random interference. Signal interference is generally unrelated to the patient's heart rate and tends to shrink in comparison to the proper pulse signal when successive pulse-by-pulse optical signals are combined.

In fact, Nellcor first introduced this concept in 1987 with its patented C-Lock™ ECG synchronization technology in the Nellcor N-200 pulse oximeter. C-Lock used a simultaneous ECG trigger to drive the synchronous averaging process. This greatly enhanced the pulse oximeter's ability to operate reliably during difficult monitoring conditions and "provide more reliable saturation measurements in a high-motion environment or when a patient has poor perfusion." Unfortunately, ECG synchronization requires the patient to be fitted with the necessary leads, and sometimes requires the pulse oximeter to be connected to an external ECG monitor.

While developing further enhancements to the algorithms found in the later N-395 and OxiMax N-595 technologies, Nellcor devised ways to implement CGA that used "virtual triggers," thereby eliminating the requirement for ECG connection and building on the advantages of this earlier experience.

In implementing the signal processing algorithms of the OxiMax N-600 pulse oximeter, Nellcor continued to draw on the strengths of these prior techniques along with incorporating further advances in microprocessing power. A brief description of the algorithms developed for the OxiMax N-600 pulse oximeter and Nellcor's latest CGA techniques follows.

### OxiMax N-600 Pulse Oximeter Advanced Signal Processing Algorithms

After acquiring and conditioning the sensor signal, the OxiMax N-600 pulse oximeter employs three independent and simultaneously running software algorithms to control the beep tone, calculate pulse rate (PR) and calculate \( \text{SpO}_2 \) values (Figure 2).

The Beep routine uses several criteria to identify and qualify individual pulses on a beat-by-beat basis (Pulse Qualification). This qualification focuses on the characteristic beat-to-beat consistency in signal pulse amplitude and recurrence, along with other metrics such as the asymmetrical shape of a proper cardiac pulse. Pulse Qualification is designed to reject, for example, pulses with abnormal shapes or periods that would be indicative of signal interference, while accepting those that are of physiological origin, including regular pulses with or without dichrotic notches and arrhythmias. This ensures that the beep tone audibly reflects the patient's current circulation without delay or averaging that may mask arrhythmias or sudden changes to the baseline rate. The beep tone also audibly reflects patient saturation level by continuously changing tone with each point change in \( \text{SpO}_2 \) value.

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Variable Cardiac Gated Averaging: Both the Pulse Rate and SpO₂ routines use CGA to process the raw red and IR waveforms. CGA processing attenuates (reduces) signal that does not occur synchronously with the average rhythm of the heartbeat. Figures 3 and 4 illustrate the principle of CGA. The incoming waveforms are broken into segments that correspond to the current pulse rate. Each segment is numerically combined with the history of prior segments to create composite signals for subsequent SpO₂ and pulse rate processing. Typically the most recent incoming pulse data contributes more to the composite signal than do the older individual pulses.

When characteristics of the incoming signal indicate that the pulses may be distorted by interference, more weight is given to the prior composite signal in the averaging process (Figure 4), further reducing the influence of the interference. Those parts of the waveform that are synchronous with the average heart rate pass through the CGA process unaffected, while signal portions not occurring with the rhythm of the heartbeat are attenuated.

The resulting CGA composite signal retains the contributions from the underlying cardiac-induced pulsations while reducing the relative influence of random interference. SpO₂ and PR values determined from the composite signal thus are more reliable. In addition to the variable-weighted CGA technology, other design elements are involved in the SpO₂, pulse rate and beep determination algorithms that assist in achieving their performance.

Conclusion

The advanced signal processing technology described here is only one of the many facets that contribute to system performance. Other integral features include a full line of OxiMax sensors, advanced user messaging, alarm management tools and remote monitoring options. Together these components, along with Nellcor’s experience in producing accurate, reliable, user-friendly pulse oximeters, give caregivers the confidence in patient monitoring they have come to expect from Nellcor.