Overview of Clinical Monitoring

1

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What Is the Purpose of Monitoring?

Why do we monitor? Monitoring, in the best circumstances, results in an improved diagnosis, allowing for more efficacious therapy. This was recognized over a century ago by the noted neurosurgeon, Harvey Cushing, to quote:

> In all serious or questionable cases the patient's pulse and blood-pressure, their usual rate and level having been previously taken under normal ward conditions, should be followed throughout the entire procedure, and the observations recorded on a plotted chart. Only in this way can we gain any idea of physiological disturbances—whether given manipulations are leading to shock, whether there is a fall of blood-pressure from loss of blood, whether the slowed pulse is due to compression, and so on. [1]

Monitoring also allows titration of medication to a specific effect, whether it is a specific blood pressure, pain level, or electroencephalogram (EEG) activity. Despite all our uses of monitoring and technologies, clear data on their benefit is limited [2, 3]. Use of monitoring may not markedly change outcomes, despite changing intermediary events. However, simple logic dictates that we still need to monitor our patients, i.e., we do not need a randomized controlled trial (RCT) to continue our practice. This was humorously pointed out in a British Medical Journal article regarding RCT and parachutes: To paraphrase, those who don't believe parachutes are useful since they haven't been studied in an RCT, should jump out of a plane without one [4]. Our ability to monitor has improved over the years, changing from simple observation and basic physical exam to highly sophisticated technologies. No matter how simple or complicated our monitoring devices or strategies, all rely on basic physical and physiological principles.

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History of Monitoring

Historically, patients were monitored by simply observing or palpating or listening: Is the skin pink? Or blue? Or pale? Palpating the pulse, is it strong, thready, etc.? Are respirations audible as well as visible? Monitoring has progressed from these large, grossly observable signals, recorded on pen and paper, to much smaller, insensible signals, and finally to complex analyzed signals, able to be stored digitally and used in control loops.

Pressure Monitoring

These first observations as referenced by Dr. Cushing involved large signals that are easy to observe without amplification (e.g., inspiratory pressure, arterial pressure, venous pressure via observation of neck veins). Pressure was one of

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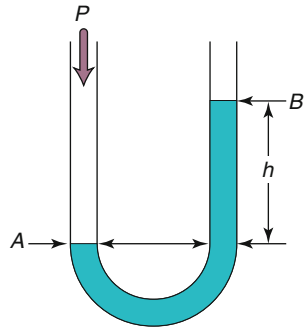

P = density • g • h,

Where density is the mass per volume of the indicator fluid, g is the acceleration of gravity, and h is the height difference between the menisci (due pressure [P]).

Fig. 1.1 Manometry. A difference in gas pressure (P) in the two arms of the manometer tube performs work by moving the indicator fluid out of the higher-pressure arm until it reaches that point where the gravitational force (g) on the excess fluid in the low-pressure arm balances the difference in pressure. If the diameters of the two arms are matched, then the difference in pressure is a simple function of the difference in height (h) of the two menisci (Reproduced from Rampil et al. [6]; with kind permission from Springer Science + Business Media B.V.)

the first variables to be monitored as the signal is fairly large, either in centimeters of water or millimeters of mercury. These historical units were physically easy to recognize and had a real-world correlate, i.e., the central venous pressure rose to a particular height in a tube marked with a scale, or the Korotkoff sounds were auscultated when the mercury column was at specific height. The use of the metric system and Systeme International is slowly replacing these units.

Monitoring pressure, while a large observable signal, is actually quite complex. In 1714 when Stephen Hales first directly measured arterial pressure in a horse by using a simple manometer, the column of blood rose to 8 ft 3 in. above the left ventricle [5]. Due to the height of the column, inertial forces, and practicality, this method is not used today. Pressures in the living organism are not static, but are dynamic and changing. Simple manometry as shown in Fig. 1.1 (allowing fluid to reach its equilibrium state against gravity in a tube) worked well for slowly changing pressures such as venous pressure, but the inertia of the fluid does not allow for precise measurement of the dynamic changes in arterial pressure [7]. Indirect measurement of blood pressure was pioneered by the method of Scipione Riva-Rocci in 1896 wherein the systolic blood pressure was determined by inflating a cuff linked to a mercury manometer until the radial pulse was absent. In 1905 Nicolai Korotkoff discovered that by auscultation, one could infer the diastolic pressure as well [5, 8]. In current use, arterial blood pressure is measured using computer-controlled, automated, noninvasive devices [9] or arterial cannulation [10] as well as the older methods. These methods may not have complete agreement, noninvasive blood pressure (NIBP) reading higher than arterial blood pressure during hypotension and lower during hypertension [11]. Use of the Riva-Rocci method (modified by using a Doppler ultrasound probe for detection of flow) has been reported to measure systolic blood pressure in patients with continuous flow left ventricular assist devices as the other noninvasive methods cannot be used [12]. What is old (measuring only systolic blood pressure by an occlusive method) is new again.

Development of pressure transducers as shown in Fig. 1.2 allowed analysis of the waveform to progress. Multiple technologies for pressure transducers exist. A common method is to use a device that changes its electrical resistance to pressure. This transducer is incorporated into an electronic circuit termed a Wheatstone bridge, wherein the changing resistance can be accurately measured and displayed as a graph of pressure versus time. Piezoelectric pressure transducers also exist which directly change their voltage output related to the pressure. These technologies, along with simple manometry, can be used to measure other pressures such as central venous pressure, pulmonary artery pressure, and intracranial pressure. The physiological importance

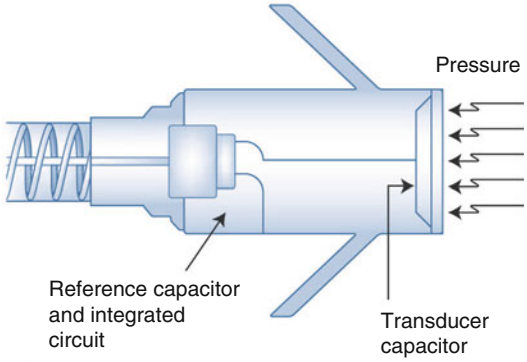

Fig. 1.2 Variable capacitance pressure transducers. Most pressure transducers depend on the principle of variable capacitance, in which a change in pressure alters the distance between the two plates of a capacitor, resulting in a change in capacitance. Deflection of the diaphragm depends on the pressure difference, diameter to the fourth power, thickness to the third power, and Young's modulus of elasticity (Reproduced from Cesario et al. [13]; with kind permission from Springer Science+Business Media B.V.)

and clinical relevance of course depends on all of these as well as the method of measurement.

Information about the state of the organism can be contained in both the instantaneous and long epoch data. Waveform analysis of the peripheral arterial signal, the pulse contour, has been used to try and determine stroke volume and cardiac output [7, 14]. Looking at a longer time frame, the pulse pressure variation induced by the respiratory signal has been analyzed to determine the potential response to fluid therapy [15]. Electronic transducers changed the pressure signal into an electronic one that could be amplified, displayed, stored, and analyzed.

Electrical Monitoring

With the advent of technology and electronics (and the elimination of flammable anesthetic agents) in the twentieth century, monitoring accelerated. Within the technological aspects of monitoring, the electromagnetic spectrum has become one of the most fruitful avenues for monitoring. Electrical monitoring yields the electrocardiogram (ECG), electroencephalogram (EEG) (raw and processed), somatosensory-evoked potentials (SSEP), and neuromuscular block monitors (simple twitch and acceleromyography). We could now measure the electrical activity of the patient, both for cardiac and neurologic signals. Computers facilitate analysis of complex signals from these monitors.

The first electrocardiogram was recorded using a capillary electrometer (which involved observing the meniscus of liquid mercury and sulfuric acid under a microscope) by AD Waller who determined the surface field lines of the electrical activity of the heart [16]. Einthoven used a string galvanometer in the early 1900s, improving the accuracy and response time over the capillary electrometer [17]. In 1928, Ernstene and Levine compared a vacuum tube amplifier to Einthoven's string galvanometer for ECG [18], concluding that the vacuum tube device was satisfactory. The use of any electronics in the operating theater was delayed until much later because the electronics were an explosion hazard in the presence of flammable anesthetics such as ether. Early intraoperative ECG machines were sealed to prevent any flammable gases or vapors from entering the area where ignition could occur.

The electroencephalogram (EEG) records the same basic physiology as the ECG (electrical activity summated by numbers of cells). However, the amplitude is tenfold smaller and the resistance much greater, creating larger technological hurdles. Using a string galvanometer, Berger in 1924 recorded the first human EEG from a patient who had a trepanation resulting in exposure of the cortex [19]. Further refinements led to development of scalp electrodes for the more routine determination of EEG. Processing the EEG can take the complex signal and via algorithms simplify it to a single, more easily interpreted number. The raw, unprocessed EEG still has value in determining the fidelity of the simple single number often derived from processed EEG measurements [20]. Somatosensory-evoked potentials can be used to evaluate potential nerve injury intraoperatively by evaluating the tiny signals evoked in sensory pathways and summating them over time to determine a change in the latency or amplitude of the signal [21].

The simple "twitch" monitor used to detect the degree of neuromuscular blockade caused by administration of either depolarizing or non-depolarizing muscle relaxants is a form of active electrical monitoring. Four supramaximal input stimuli at 0.5-s intervals (2 Hz) stimulate the nerve and the response is observed. Rather than simply seeing or feeling the "twitch," a piezoelectric wafer can be attached to the thumb and the acceleration recorded electronically. Acceleromyography may improve the reliability by decreasing the "human factor" of observation as well as optimizing the muscle response if combined with preloading of the muscle being stimulated [22]. Understanding that electromagnetic waves can interfere with each other explains some of the modes of interference between equipment [23].

Light Monitoring

Many gases of interest absorb light energy in the infrared range. Since multiple gases can absorb in this range, there can be interference, most notably for nitrous oxide [24], as well as false identifications. Intestinal gases such as methane can interfere as well [25]. Capnography has multiple uses in addition to detecting endotracheal intubation in the operating room, such as detection of cardiac arrest, effectiveness of resuscitation, and detection of hypoventilation [26]. In the arrest situation, it must be remembered that less CO_2 is produced, and other modalities may be indicated, such as bronchoscopy, which uses anatomic determination of correct endotracheal tube placement rather than physiological [27].

Pulse oximetry utilizes multiple wavelengths, both visible and IR, and complex processing to result in the saturation number displayed. In its simplest form, pulse oximetry can be understood as a combination of optical plethysmography, i.e., measuring the volume (or path length the light is traveling), correcting for the non-pulsatile (non-arterial) signal, and measuring the absorbances of the different species of hemoglobin (oxygenated, deoxygenated). The ratio of absorbances obtained is empirically calibrated to determine the percent saturation [28]. The use of multiple wavelengths can improve the accuracy of pulse oximetry and potentially provide for the measurement of other variables of interest (carboxyhemoglobin, methemoglobin, total hemoglobin) [29, 30].

Acoustic Monitoring

Sound is a longitudinal pressure wave. Auscultation with a stethoscope still has a place in modern medicine: An acute pneumothorax can be diagnosed by auscultation of decreased breath sounds, confirmed by percussion and hyperresonance, and treated by needle decompression (completing the process). A "simple" stethoscope actually has complex physics behind its operation. The bell and diaphragm act as acoustic filters, enhancing transmission of some sounds and impeding others to allow better detection of abnormalities [31].

Modern uses of sound waves have increased the frequency of the sound waves used to improve the spatial and temporal resolution, providing actual images of the internal structures in three dimensions [32]. Now only of historical use, A-mode ultrasonography (standing for amplitude mode) displayed the amplitude of the signal versus distance, useful for detecting a pericardial effusion or measuring fetal dimensions. B-mode ultrasound stands for "brightness mode" and produced a "picture" where the amplitude was converted to brightness. Multiple B-mode scans combine to produce the now common two-dimensional ultrasonography. M-mode echo displays the "brightness" over time, giving very fine temporal resolution [33]. These are still subject to physical limitations, i.e., sound transmission is relatively poor through air or bone (hence, the advantage of transesophageal echocardiography (TEE) vs. surface echocardiography), and fast-moving objects are better resolved using M-mode echo. The Doppler principle, involving the shift in wavelength by moving objects, can be used to detect and measure blood velocity in various vessels.

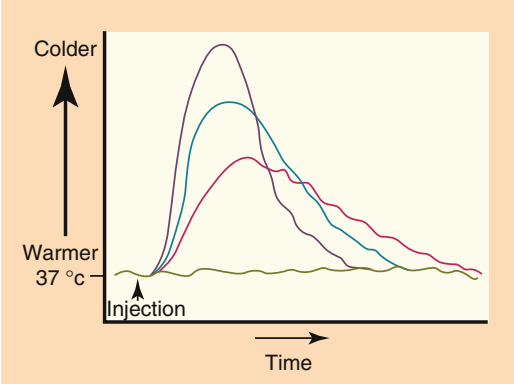

Fig. 1.3 Thermodilution for cardiac output measurement via Stewart-Hamilton indicator-dilution formula. The integral of change in temperature (area under the curve) is inversely related to cardiac output. A smooth curve with a rapid upstroke and slower delay to baseline should be sought. Sources of error include ventilatory variation, concurrent rapid-volume fluid administration, arrhythmias, significant tricuspid or pulmonary regurgitation, intracardiac shunt, and incomplete injection volume (causing overestimation of cardiac output). Lower cardiac output states result in relative exaggeration of these errors. Intraoperatively, ventilation can be temporarily suspended to measure cardiac output during exhalation, and several measurements should be averaged. If a second peak in the thermodilution curve is seen, a septal defect with recirculation of cooled blood through a left-to-right shunt should be suspected (Reproduced from Field [34]; with kind permission from Springer Science + Business Media B.V.)

Temperature Monitoring

Common household thermometers use liquid (or a combination of metals) that expands with heat, obviously impractical for intraoperative monitoring. For continual monitoring, a thermistor is convenient. A thermistor works as part of a Wheatstone bridge, wherein the change in resistance of the thermistor is easy calibrated and converted into a change in temperature. Small, intravascular thermistors are used in pulmonary artery catheters for thermodilution monitoring of cardiac output as shown in Fig. 1.3. Newer electronic thermometers use IR radiation at the tympanic membrane or temporal artery. Unfortunately, despite ease of use, the accuracy is not as good as other methods [35].

Chemical Monitoring

Glucose was one of the first chemistries monitored in medicine, being related to diabetes [36]. The evolution of glucose measurements parallels that of many other measurement values, starting with chemical reagents, such as "Benedict's solution," mixed in actual test tubes, to miniaturization, to enzyme associated assays. Current point-of-care glucometers were primarily designed for home use and self-monitoring and their accuracy can be suspect [37]. But controversy and disagreement between different methods of measurement is a long-standing tradition in medicine [38].

Blood gas analysis began with the Clark electrode for oxygen in the early 1950s [39], followed by Severinghaus electrode for CO_2 in the late 1950s [40, 41]. Other ions (calcium, sodium, etc.) can be measured by using ion-selective barriers and similar technologies. Most chemical measurements involve removing a sample from the patient. Optode technology allows continuous, invasive measurement directly in the patient. This technology uses optically sensitive reagent exposed to the body fluids via a membrane, and the information transmitted via a fiberoptic cable [42–44]. Advantages to these continuous techniques have yet to be seen.

Respiratory carbon dioxide was identified by chemist Joseph Black in the 1700s. He had previously discovered the gas in other products of combustion. Most respiratory analysis is done by infrared absorption. (Oxygen is a diatomic gas and does not absorb in the infrared range so either amperometric fuel cell measurements or paramagnetism is used.) Exhaled carbon dioxide can be detected and partially quantitated in the field by pH-induced color changes, akin to litmus paper. Of note, gastric acid can produce color changes suggestive of respiratory CO_2, providing a false assurance that the endotracheal tube is in the trachea, not in the esophagus [45]. More information is provided using formal capnography [27].

Point-of-care testing uses different reactions than standard laboratory test and results may not be directly comparable [46]. A test may be both

accurate and precise, but not clinically useful in a particular situation. Measurement of a single value in the coagulation cascade may contain insufficient information to predict the outcome of an intervention. For example, antiphospholipid antibodies can increase the measured prothrombin time, while the patient is actually hypercoagulable [47].

Flow Monitoring

> It is a source of regret that the measurement of flow is so much more difficult than the measurement of pressure. This has led to an undue interest in the blood pressure manometer. Most organs, however, require flow rather than pressure…
>
> Jarisch, 1928 [48]

Flow is one of the most difficult variables to measure. The range of interest can vary greatly, from milliliters per minute in blood vessels to dozens of liters per minute in ventilation. Multiple techniques can be used to attempt to measure flow. Flow in the respiratory system and the anesthetic machine can be measured using variations on industrial and aeronautical devices (pitot tubes, flow restrictors combined with pressure sensors) and have an advantage that the flow can be directed through the measuring device. Cardiac output and organ flow are much more difficult to measure.

Adolf Fick proposed measuring cardiac output in the late 1800s using oxygen consumption and the arterial and venous oxygen difference [49]. A variation of this method uses partial rebreathing of CO_2. Most measures of cardiac output are done with some variation of the indicator-dilution technique [14, 50]. Most techniques do not measure flow directly, but measure an associated variable. Understanding the assumptions of measurement leads to a better understanding of the accuracies and inaccuracies of the measurement. Indicator-dilution techniques work via integrating the concentration change over time and can work for various indicators (temperature, carbon dioxide, dyes, lithium, and oxygen) with different advantages and disadvantages. Temperature can be either a room temperature or ice-cold fluid bolus via a pulmonary artery catheter (with a thermistor at the distal end) or a heat pulse via a coil built into the catheter. Similar to injecting a hot or cold bolus, chemicals, such as lithium, can be injected intravenously and measured in an arterial catheter and the reading converted to a cardiac output [51]. An easy conceptual way to picture the thermodilution techniques (and to determine the direction of an injectate error) is to imagine trying to measure the volume of a teacup versus a swimming pool by placing an ice cube in each. The temperature change will be much greater in the teacup because of its smaller volume (correlates to the flow or cardiac output) than in the swimming pool. Decreasing the amount of injectate or increasing its temperature will overestimate the volume.

Measuring cardiac output by Doppler technique involves measuring the Doppler shift, calculating the velocity of the flow, measuring the cross sectional area and ejection time, and calculating the stroke volume. Then cardiac output is simply stroke volume times heart rate, assuming the measurement is made at the aortic root. Most clinical devices measure the velocity in the descending aorta and use a nomogram or other correction factors to determine total output [52].

Processed Information

Monitoring has progressed from large, grossly observable signals, recorded on pen and paper, to much smaller, unable to be sensed signals, and finally to complex analyzed signals, able to be stored digitally and used in control loops.

Data when obtained from monitoring can be stored using information systems or further analyzed in multiple manners. Processed data can reveal information that is not otherwise apparent. The SSEP can use data summation to elucidate a signal from a very noisy EEG background. Other processed EEG methods to measure depth of anesthesia use combinations of Fourier transform, coherence analysis, and various proprietary algorithms to output a single number indicating depth. Pulse oximetry and NIBP are two common examples of a complex signal being simplified into simpler numbers. Pulse contour analysis

attempts to extract stroke volume from the arterial waveform [53].

Interactive monitors (where the system is "pinged"), either via external means (NMB monitor, SSEP) or internal changes (systolic pressure variation, pulse pressure variation, respiratory variation), can be thought of as "dynamic indices" wherein the information is increased by monitoring the system in several states or under conditions of various stimulation [54].

Automated feedback loops have been studied for fluid administration, blood pressure, glucose, and anesthetic control [55–57]. Even if automated loops provide superior control under described conditions, clinically humans remain in the loop.

Conclusion

Although monitoring of patients had been ongoing for years, the ASA standards for basic anesthetic monitoring were first established in 1986 and periodically revised. Individual care units (obstetric, neuro intensive care, cardiac intensive care, telemetry) may have their own standards, recommendations, and protocols.

While not all monitoring may need to be justified by RCT, not all monitoring may be beneficial. The data may be in error and affect patient treatment in an adverse manner. Automated feedback loops can accentuate this problem. Imagine automated blood pressure control when the transducer falls to the floor: Sudden artifactual hypertension is immediately treated resulting in actual hypotension and hypoperfusion.

All measured values have some variation. Understanding the true accuracy and precision of a device is difficult. We have grown accustomed to looking at correlations, which provide some information but give a "good" value merely by virtue of correlation over a wide range, not true accuracy nor precision. A Bland-Altman analysis provides more information and a better method to compare two monitoring devices, by showing the bias and the precision. The Bland-Altman analysis still has limitations, as evidenced by proportional bias, wherein the bias and precision may be different at different values [58]. Receiver operator curves are yet another manner of assessment for tests that have predictive values.

The ultimate patient monitor would measure all relevant parameters of every organ, displayed in an intuitive and integrated manner; aid in our differential diagnosis: track ongoing therapeutic interventions; and reliably predict the future: the ultimate patient monitor is a physician.

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