Review

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Computerized Analysis of Antepartum Cardiotocography: A Review

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Abstract

Cardiotocography measures the human fetal heart rate and uterine activity using ultrasound. While it has been a mainstay in antepartum care since the 1960s, cardiotocograms consist of complex signals that have proven difficult for clinicians to interpret accurately and as such clinical inference is often difficult and unreliable. Previous attempts at codifying approaches to analyzing the features within these signals have failed to demonstrate reliability or gain sufficient traction. Since the early 1990s, the Dawes-Redman system of automated computer analysis of cardiotocography signals has enabled robust analysis of cardiotocographic signal features, employing empirically-derived criteria for assessing fetal wellbeing in the antepartum. Over the past 30 years, the Dawes-Redman system has been iteratively updated, now incorporating analyses from over 100,000 pregnancies. In this review, we examine the history of cardiotocography, signal processing methodologies and feature identification, the development of the Dawes-Redman system, and its clinical applications.

Keywords: Antepartum; Cardiotocography; Computerized; Electronic fetal monitoring; Fetal monitoring

Introduction

Cardiotocography (CTG), also known as electronic fetal monitoring, is the non-invasive measurement of the fetal heart rate (FHR) and uterine activity. Understanding the physiology of the FHR and how it manifests in CTG enables us to infer the physiological state of the baby and assess the requirement for intervention. This is primarily achieved through the identification of unique patterns in the signal (eg, accelerations and decelerations). Features within the CTG signal enable identification of pathological states such as systemic hypoxia and acidemia and its consequence for the fetal cardiovascular and other organ systems. This allows risk assessment of adverse fetal outcomes and understanding of gradations of fetal stress and stress responses. However, these features are difficult, if not impossible, for a human interpreter to accurately identify reliably and consistently. Moreover, the interactions between different features in high-risk clinical settings can be particularly difficult to assess. At present a CTG cannot reliably diagnose fetal disease, instead it can identify a "normal" fetus based on empirical observations. The aim of this review is to explore the signal processing, feature identification, and analysis algorithms in computerized CTG with a focus on the long-established Dawes-Redman (DR) system and its clinical uses.[1]

Fetal behavioral states, sleep and central nervous system control of the FHR

Early studies of neonatal movements revealed certain repetitive patterns which were termed behavioral states. These were stereotyped clusters of activity, which recurred several times during one day (ultradian), and were seen in all cases. They comprised fast and complete transitions or switching from one state to another. When ultrasound became available it was evident that the fetus developed similar states as it matured during the second half of pregnancy.[2] Probably the most important of these states was sleep. Two phases of fetal sleep were quickly demonstrated: active and quiet, with which fetal medicine practitioners are now familiar. Important for this review is that FHRs changed as the sleep states switch and dominate how CTG patterns are interpreted.

There are other components of the behavioral states of which some are associated with characteristic CTG patterns including: fetal hiccups, sinus arrhythmia, breathing movements, sucking, yawning, and most important fetal body movements.[3,4]

Healthy fetuses cycle between episodes of active and quiet sleep usually 1–3 times per hour at term. It is not known what arouses a fetus from quiet sleep. It involves sympathetic activation which may be physiological or provoked by acute stress.[5] Hallmark features of active sleep include a cluster of features that include accelerations, fetal movements, and episodes of high FHR variation.[6] These can be used as a primary indicator of fetal wellbeing. Conversely, quiet sleep is associated with episodes of low FHR variation and decreased fetal movements, which can be confused with fetal compromise.

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Behavioral states reflect complex CNS integration, involving the cerebral cortex, mid-brain (particularly the hypothalamus), and brain stem as well as the autonomic nervous system more peripherally.[7]

At the lowest level is the spinal autonomic nervous system, which is part of the peripheral nervous system. It has many functions that include regulation by reflexes activated in the brain stem. These depend primarily on baroreceptors and chemoreceptors that act through parasympathetic (vagal) and sympathetic reflex pathways. A cardioacceleratory center connects via sympathetic cardiac nerves to the sinoatrial node to increase the FHR, whereas a cardioinhibitory center reduces the FHR via the parasympathetic vagus nerve.

Arterial baroreceptors detect vascular distension caused by blood pressure changes. An increase in blood pressure (for example due to umbilical cord compression) triggers a signal to the cardioinhibitory center that rapidly induces a parasympathetic reduction in FHR. Chemoreceptors located in the brainstem are sensitive to low blood pH and elevated pCO_2 levels (eg, acidaemia), while peripheral chemoreceptors are sensitive to low pO_2 (ie, hypoxia).

Fetal chemoreceptors activate strong sympathetic responses from the CNS, inducing peripheral vasoconstriction and redirecting blood volume to vital organs. At the same time a vagal parasympathetic response decreases the heart rate, which may be clinically recognized as a deceleration. This coordinated effort temporarily reduces myocardial work to compensate for low oxygen availability.[8,9] Adrenaline, noradrenaline, and vasopressin are also secreted into the fetal circulation, which promote a systemic vascular response. Noradrenaline increases heart rate, contractility, and stroke volume, as well as redistributing of blood volume through vasoconstriction (alpha-adrenergic receptors), and vasodilation (beta-adrenergic receptors) in different regions. These autonom-ic reflexes determine short term changes in the heart rate.

These reflexes are in turn regulated by centers in the mid-brain and cerebral cortex. A key cardiovascular controller is the paraventricular nucleus of the hypothalamus which is adjacent to the suprachiasmatic nucleus which controls sleep.[10,11] Arousal from sleep is mediated by the sympathetic nervous system although its involvement in human fetal activity has yet to be demonstrated directly.

The rapidity of heart rate change is correlated with the rapidity of conditions that trigger these reflexes: direct neuronal pathways from the CNS induce a sudden alteration in heart rate within seconds, while slower hormone-based reflexes manifest within several minutes. All of these systems possess one unified objective: adequate oxygen supply to the fetal organs, without which fetal compromise and death will occur.

The importance of fetal sleep and other behavioral states has been emphasized here because they dominate the interpretation of the antepartum CTG, whether visually or by computerized analysis.

It can be concluded that the CTG is an indirect fetal brain test. Any condition that affects the fetal brain may lead to changes in the CTG: for example thrombotic stroke or administration of CNS depressants to the mother. It is not just fetal hypoxia.

The DR computerized CTG system pioneered the concept of identifying CTG patterns that reflect fetal sleep states. This is described in ensuing sections.

Development of early CTG devices

Continuous electronic recordings of FHRs and uterine contractions began to be developed in the early 1950 s.[12] These early systems required direct attachment of the electrode probe to the fetal scalp once membranes had ruptured, limiting their use primarily to intrapartum monitoring.[13,14] Subsequently a microphone system to capture sounds generated by the fetal heart allowed passive, external recording from 24 weeks gestation. This was the first commercial antepartum CTG recording apparatus, available from 1968: the Hewlett-Packard 8020A. It suffered from substantial interference because of its sensitivity to environmental noise.[15] In 1971, the Hewlett-Packard 8021A electronic fetal monitoring system, used an ultrasound transducer strapped to the maternal abdomen to detect movement of fetal heart valves. This attenuated interference by environmental sound and allowed more freedom in maternal positioning. Thereafter, ultrasonic CTG became the general standard for continuous intrapartum electronic fetal monitoring. Over the next 10 years understanding and analysis of the FHR would be achieved, and the introduction of noninvasive ultrasonic CTG would be associated with up to an 80% decline in intrapartum stillbirths.[16] However, early in the development of cardiotocographs, there was acknowledgment that human visual interpretation of CTG signals would overlook some information.[17] With longer recordings, it becomes impossible to retain a clear idea of the witnessed events and automated data processing was suggested as the means by which to address some of the inherent problems suffered by CTG.[17,18] There was also the clear need for data reduction methodologies (reducing the large amount of information to a small number of representative data), quantification (expressing features in the signal in quantitative units), presentation of analysis (presenting the results of analysis to the investigator in an surveyable format – graphs, figures, printed text) and trend detection (rapid comparison of several parts of the recording, facilitated by the reduced signal to check the changes in the recorded data and to correlate these alterations with the condition of the fetus).

Human visual assessment of antepartum CTG records

CTG patterns are complex. It is well-established that subjective assessment of these patterns suffers from poor inter-observer and intra-observer reproducibility. This is true of both antepartum and intrapartum records. Early studies comparing expert human visual analysis and computer analysis showed that humans failed to identify 35% of traces with none or one acceleration, failed to detect 92% of decelerations and that interobserver variability is high, further bolstering the belief that computerized analysis could overcome these issues.[19,20] Even when experts implement modern FIGO guidelines, the reproducibility of event analysis is poor and the

agreement on subsequent clinical decisions is inconsistent.[21–23] Initially, this was due to a lack of consensus on how to best analyze and describe these traces. Several early methods were proposed, including the use of scoring systems and risk indices that would attribute values to different features that could be identified within the trace, however, few succeeded in becoming widely adopted.[24–32] Early studies to determine the reproducibility of CTG analysis and its diagnostic value used differing scoring criteria and focused on different features.[33–36] Further, low levels of inter-observer agreement (as low as 29%)[35,37] for each of these proposed methods meant comparison between different proposed systems proved cumber-some. Conversely, studies assigning CTGs into a more diverse range of normal or pathological outcomes instead showed that with an increasing number of categories the reliability of CTG interpretation deteriorates even further.[38] The reliability of interpretation performs, at best, "fairly" with simple models but much worse with more complex models and this increased complexity negatively affects reliability. Interobserver reliability remains poor even between "expert" observers, an observation which is consistent across different medical departments and geographic regions internationally.[36,39,40] Over the years, numerous studies have drawn attention to the critical need for scientific clarification as to which FHR patterns are the best predictors of fetal distress and the need for a gold standard method of analysis,[38,40] as the suggested clinical management scenarios based on FHR assessment also show poor agreement among experts.[41] Unsurprisingly, studies have demonstrated that failure to interpret abnormal CTG recordings accurately directly correlates with fetal death.[42] These problems could and can be solved by objective numerical measurement of the relevant CTG features, which requires computerization of the basic signals produced by the CTG device.

Signal pre-processing

Raw ultrasonic CTG signals require robust signal pre-processing methodologies.[43] This mode of CTG is an indirect measure of fetal heart activity and the signal inherently suffers from noise and interference, as it must first travel from the fetal heart valves, through the several tissue layers (placenta, uterus, viscera, and anterior abdominal wall) before detection by the ultrasound probe. This results in a poorer signal-to-noise ratio compared with direct intra-abdominal fetal electrocardiography. Further, at the time CTG was being introduced into clinical practice, data storage capacity was measured in kilobytes and computer processors were a small fraction of modern speeds. The Hewlett-Packard 8030A CTG would sample at ~2 MHz (2000 times per second), while a recording of a FHR at 150 beats per minute would result in 9600 samples for a 64 minute record – the standard recording length at the time.[44] This was problematic for a computer system that only had a storage capacity of several megabytes. Due to the extensive recording lengths of CTGs and the obvious wealth of information they contained, it was soon realized that human visual analysis of the signal on pieces of paper tape could, at best, result in the identification of gross morphological features while maintaining a reliable survey of the entire record was almost certainly impossible.[17] Automatic processing of data could reduce the excessive amount of information present, provide discrete quantification of the information, present the information in a more easily interpretable format and facilitate simpler detection of trends throughout the trace, irrespective of the recording length.

Computerized analysis of CTG signals

Before robust signal processing methods were developed, minor forays into computerized analysis of the FHR were made through the development of indices for short-term variation (STV) and long-term variation (LTV); however, these were unable to incorporate other features. High variation in FHR traces had been proposed as early as 1968 as a predictor of fetal health, but there was no proposed process of robust and consistent measurement.[45,46] In 1991, Geoffrey Dawes and Christopher Redman of Oxford University unveiled the System 8000: the first complete computerized method pipeline for antepartum CTG signal processing and analysis, developed from approximately 20,000 CTG records since 1982 for use between 30 and 41 weeks gestation.[44,47,48] The system was capable of real-time analysis of CTG signal traces with a minimal lag time between signal acquisition and display of analysis results. The advantages of this system were numerous, including increased accuracy and temporal resolution, quantitative analysis and display of results for clinical interpretation, comparison of measurements with predetermined normal values, unambiguous description of FHR traces, absolute consistency and reproducibility, and potential for correlation with other fetal disease states.[49] This system could also reduce recording times through recommending cessation of recording if an episode of high variation was identified after 10 minutes. The DR system would display results in a way that facilitated simpler analysis of emerging trends, not only throughout the recording, but also over time between different recordings acquired at different gestational ages. The System 8000 has undergone significant upgrades since its inception, now honed by over 100,000 antepartum CTG recordings and employing the DR criteria: the international gold standard for antepartum CTG analysis, comprising 10 unique criteria for assessment.[1] It is used not only in the UK but France, Spain, Russia, Australia, and China and has been included in national healthcare guidelines.[50] A summary of the CTG features identified by the DR system is in Table 1.

The DR system analyses data averaged into epochs lasting 3.75 seconds

CTG ultrasound signals often contain missing or erroneous information. To address this problem the DR Analysis System requires additional data "cleaning", which is achieved by outlier removal, signal averaging, filtering, interpolation and autoregression. The FHR is derived by measuring the interval between consecutive pulses. When the DR system was first developed, it was necessary to average the pulse intervals over 3.75 second epochs owing to limitations of data storage and processing speeds. This

Table 1

Criteria for fitting a FHR baseline.

Criteria for identifying the baseline FHR
1) The pulse interval (PI) represents at least 0.5% of the total count of pulse intervals OR PI does not differ from the highest recorded pulse interval by >30 milliseconds
2) The frequency of the PI is > the frequency of the lower 5 pulse intervals
3) PI sits in the lower 87.5% of the frequency distribution of all pulse intervals
If these criteria are not met, the mode of the pulse intervals is used.

The pulse interval used to determine the baseline FHR is identified using 3 criteria. If these criteria cannot be met, the mode pulse interval is chosen.
FHR: Fetal heart rate.

time interval was empirically determined to be the maximum possible duration that did not distort accelerations or decelerations identified within the signal. Data reduction of this kind has its limits. If it is excessive it ceases to be a valid reflection of the original signal such that clinical inference is no longer possible. Valid fetal heart pulses within each epoch are then used to calculate the mean heart rate within that epoch. These epochs are then additionally filtered to remove large transient changes of heart rate (≥25 bpm) that quickly return to the previous mean heart rate, which are typical of signal artifacts and unlikely to be a deceleration or acceleration. The number of invalid fetal heart pulsations (eg, missing or outlier FHR values) and removed epochs are summed to measure "failure time" or signal loss that reflects signal quality. Further refinements in signal processing yielded up to a 10-fold reduction in signal loss.[51–53] While this procedure might now appear straightforward, it was the first robust signal preprocessing methodology ever developed for CTG, facilitating a 16-fold reduction in the number of required heart pulse samples for a clinically reliable recording and enabled, for the first time, storage and analysis of CTG databases on commonplace computer systems. These procedures continue to be employed today.

The importance of signal loss

Signal loss of CTG recordings depends on gestational age. In recordings 64 minutes long, signal loss decrease from approximately 44.9% at 16–19 weeks to 18.1% at 41 weeks. There is no clear consensus on why there is a gestational-age dependent amount of signal loss; however, interestingly, there is no discernible difference in failure times between normal and high-risk pregnancies, suggesting the role of pathology does not contribute to the probability of a loss in signal during recording.[54] Further, although this quantification of failure time appears large, visual analysis of the signal during recording was noted by clinicians to be adequate for visual analysis and these apparently large amounts of invalid heart rate measurements seemed to mostly go unnoticed on paper printouts of the CTG signal. This is believed to be due to the observation that extended periods of failure that could be noticed visually actually occur rarely and the resolution of the display of a CTG recording does not allow for an accurate appraisal of these missing data points. While averaging heart rates across 3.75 second intervals aids in reducing these failure rates, high failure times are not associated with longer sequences of invalid measurements, and rarely do sequences of invalid periods of invalid epochs extend beyond 11.25 seconds (3 epochs). Perhaps counterintuitively, there is no strong association between signal loss and specific heart rate patterns, fetal movements, or fetal breathing. The only correlation identified between failure time and FHR patterns is during episodes of high signal variation (discussed later), when mean signal loss is greater, compared with episodes of low variation. The proposed cause of this is a more mobile fetus (when episodes of high variation associated with movement may be lost) or hiccoughs.[53] However, it appears that patterns of signal loss are common and the overall process sporadic. Thus, the amount of signal loss observed for any given CTG recording should not be incorporated as a measure of fetal distress. The DR method of signal analysis provides a unit measurement of the signal quality to inform clinical decision making.

Baseline FHR

The baseline FHR is the average FHR in a given time window, excluding any major deviations. The baseline is the reference point for the entire trace and facilitates identification of features within the recording such as accelerations and decelerations. Human visual analysis of the CTG record is unable to fit the baseline heart rate as accurately and .iteratively as computerized analysis. The DR system for fitting the baseline was empirically derived and validated using 73,802 CTG records. The initial baseline is determined by filtering the first ten minutes of the signal with a band pass filter (a filter that only allows heart rates through within a certain range, thus reducing noise). The upper and lower edges of this filter are determined by choosing the most frequently occurring (epoch-wise) average pulse interval for the first ten minutes of the recording that meet three criteria (Table 1). The upper and lower limits of the band pass filter are then set as ± 60 milliseconds of the selected pulse interval (Fig. 1). This filter is used to fit a rolling baseline that iteratively updates as the recording progresses. Sudden, rapid changes in the baseline beyond the range of 60 milliseconds have been observed in approximately 0.01% of recordings, which are accounted for by refitting the baseline for any signals in which the FHR fails to return to the previous baseline in a 10-minute window.[55] This approach to identifying the baseline FHR has proven superior to manual human methods that can often be made more difficult due to sudden and transient departures from the baseline, the presence of minor accelerations or decelerations, density of FHRs on display monitors or paper printouts, as well as inherent variability in the FHR within the normal range.

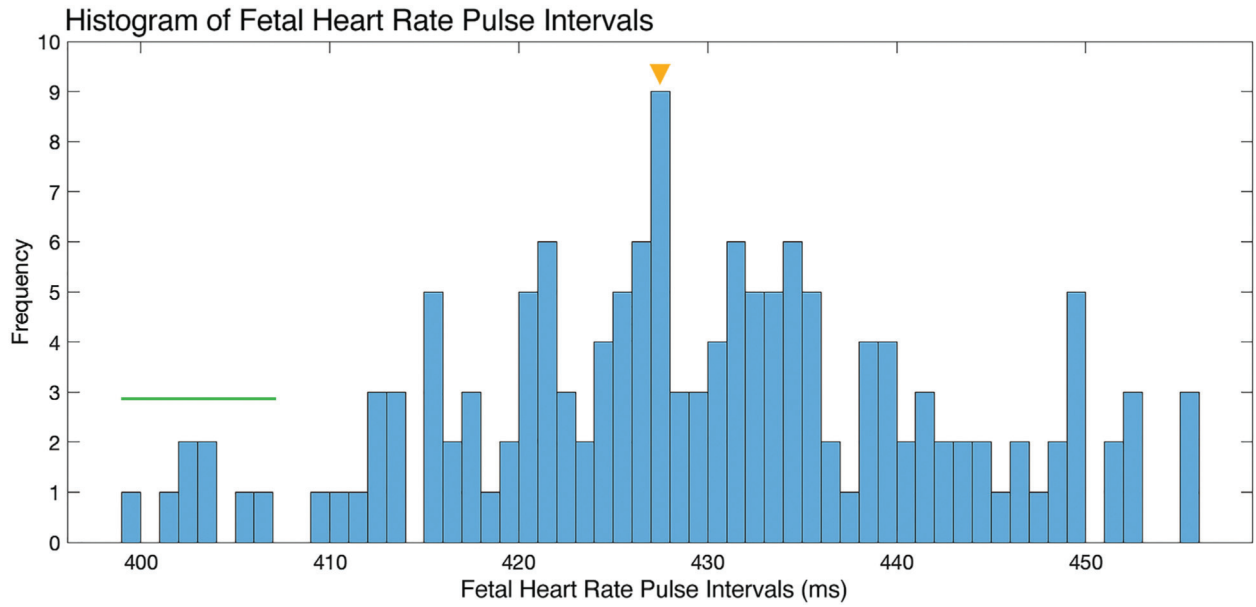

Figure 1. Fitting a baseline using the Dawes-Redman method (Table 1). The most frequently occurring pulse interval is 427 ms (~140 bpm, orange arrow) and occurs in 6.08% of all pulses in the first ten minutes. The frequency of the lower five pulse intervals is less than the frequency of the most frequently occurring pulse interval (seven, green line). The PI sits in the lower 87.5% of the frequency distribution of all pulse intervals. Therefore, the parameters of the bandpass filter applied to this CTG recording would be 427 ± 60ms, or (367,487), corresponding to a FHR range of 123–163 bpm. This is then iteratively updated as the recording progresses. bpm: Beats per minute; CTG: Cardiotocography; FHR: Fetal heart rate; PI: Pulse interval.

Accelerations and decelerations

Accelerations and decelerations are transient deviations above or below the baseline FHR. These can be measured in amplitude (amount of deviation in FHR from the baseline FHR), duration, or total beats lost (the product of amplitude and duration). In the DR system, an acceleration is defined as a transient increase in the FHR at least 10 bpm above the baseline lasting longer than 15 seconds (beats gained ≥150), while a deceleration is either a transient decrease of at least 20 bpm lasting longer than 30 seconds or at least 10 bpm lasting longer than 60 seconds (beats lost ≥600). These patterns can be identified immediately by the computerized analysis system (Fig. 2), whereas in human visual analysis this is a more subjective process, first requiring mentally fitting the baseline and manually counting each lost or gained beat to identify the pattern – an obvious source of potential error, especially in a clinical environment. Moreover, the pattern of these accelerations and decelerations evolve throughout gestation.

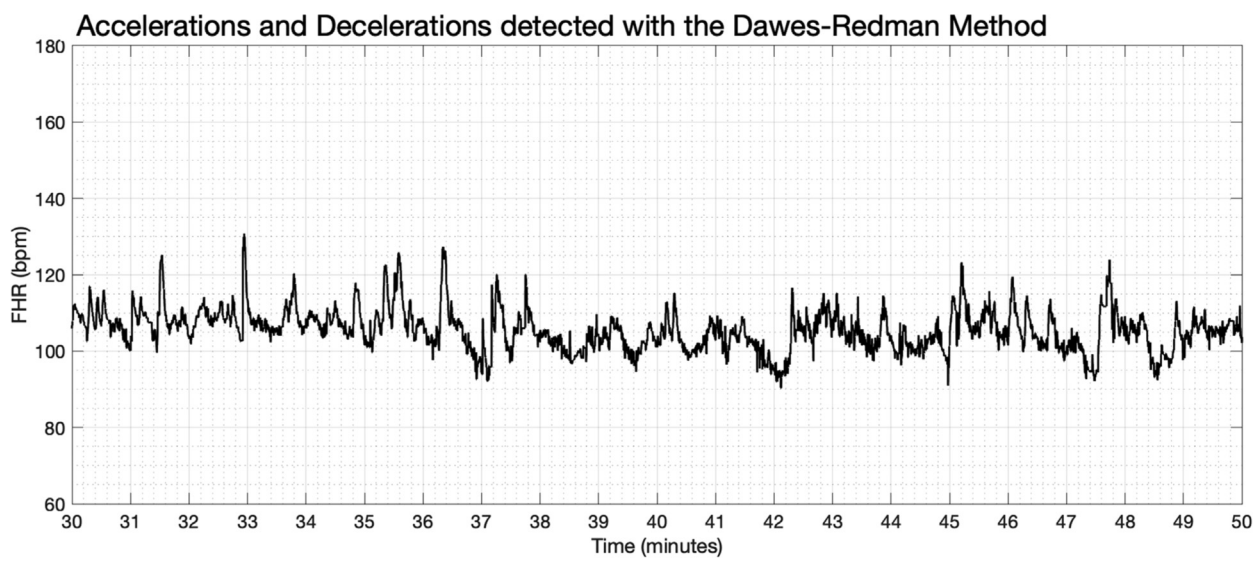

Figure 2. An example of a complex antepartum CTG signal containing clustered accelerations and decelerations. This signal contains large decelerations, some with >20 lost beats per minute or lasting up to one minute. These patterns were identified with the Dawes-Redman computerized CTG system after baseline fitting. This CTG was performed on a singleton pregnancy at 35 weeks gestation and the fetus was delivered at 40 weeks without any adverse outcomes. bpm: Beats per minute; CTG: Cardiotocography; FHR: Fetal heart rate.

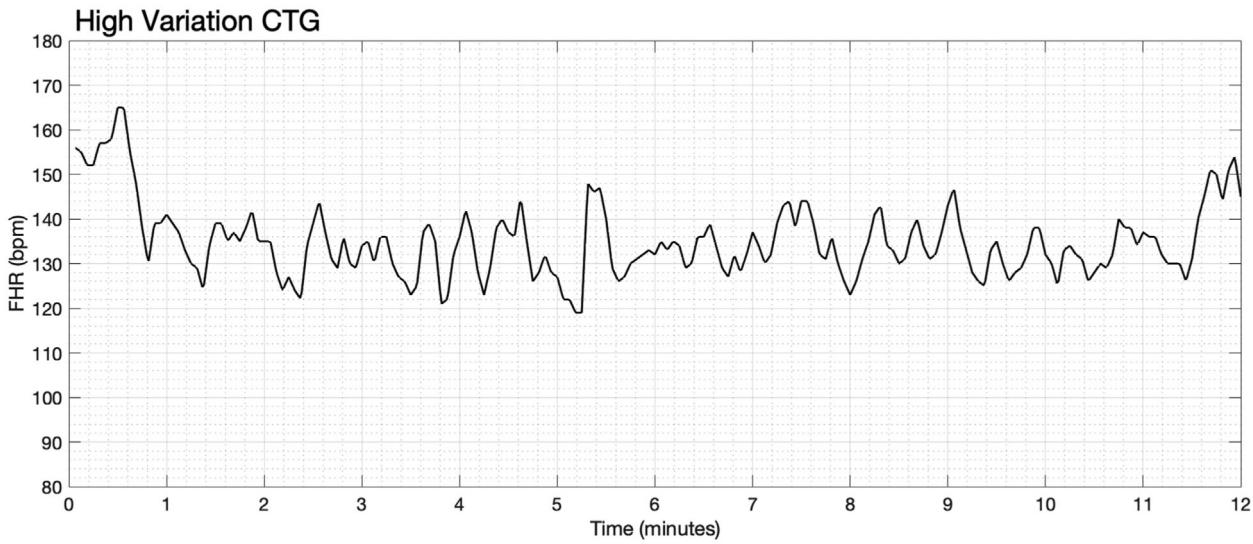

Figure 3. Episodes of high variation in a fetus at 37 gestational weeks. The short-term variation was 13.35 ms and the long-term variation 70.60 ms. This record contains three accelerations, no decelerations, and no episodes of low variability. This fetus had normal outcomes. bpm: Beats per minute; CTG: Cardiotocography; FHR: Fetal heart rate.

With increasing gestational age, accelerations and decelerations are observed to cluster into episodes[54] (Fig. 2). Prior to 30 weeks gestation, the area of a deceleration is greater than an acceleration; thereafter this relationship reverses[56] and accelerations are believed to be an indicator of fetal wellbeing.[56] However, while the incidence of accelerations increases with gestational age along with the average size of accelerations, they may be completely absent in up to 40% of CTG records of normal pregnancies. Thus, relying solely on the presence of an acceleration may result in unnecessarily prolonged recording times.

Decelerations are a problematic feature due to their frequent regard as indicators of poor fetal health or compromise, however, decelerations have also been associated with continuing central nervous system medullary function when coupled with decreasing FHR varia-tion.[48] Further, large decelerations of around 100 bpm in otherwise normal CTGs are often associated with the fetus switching from a state of high FHR variation to low FHR variation (discussed further on). This is characteristic of a change in fetal sleep state, not with an increased risk of poor outcome, as is often believed with the presence of decelerations. Decelerations of <20 lost beats have been shown to have no predictive value for poor outcome if FHR variation is within normal range.[57]

As such, there is no concrete clinical consensus on their interpretation, even though they are often integrated into modern guidelines on CTG analysis.[23] Thus, human interpretation of these patterns is difficult, as it requires the observer to keep these complex nuances in mind, some of which are almost indiscernible to the average practitioner. Importantly, the DR system is capable of removing "false features", such as accelerations or decelerations containing more than 50% signal loss as well as errors such as abrupt deviations >35 bpm from the baseline with equally abrupt returns to baseline,[48] attenuating this uncertainty.

Episodes of low and high variation

FHR variation (also referred to as variability) is the measure of deviation or oscillation of the heart rate above and below the baseline in a given time span. As described earlier, FHRs demonstrate prolonged, recurrent periods of high and low variation from the third trimester and are of important clinical value[2,58,59] (Fig. 3). The hallmark CTG patterns of active sleep are distinctive, comprising accelerations, clustered fetal movements, and episodes of high FHR variation, which can be used as a primary indicator of fetal wellbeing. However, quiet sleep, associated with episodes of low FHR variation and decreased fetal movements, can be confused with fetal compromise.

The assessment of fetal wellbeing during quiet sleep is difficult, if not impossible with current technologies. Progressive decline in FHR variation is the most useful sign of a deteriorating fetal health between 24–38 weeks gestation[55] and low FHR variation in a healthy fetus during an episode of quiet sleep cannot be distinguished from this.[60,61] If a recording is commenced at the beginning of an episode of quiet sleep (and therefore period of low variation), monitoring must proceed until an episode of active sleep is identified to rule out a nonreactive trace. This can require up to 60 minutes of recording time in healthy fetuses.[2,62–64]

These recurrent episodes of high and low variation are related to the cyclic changes in fetal activity from as early as 24 weeks.[2,56,59,65] From 27 weeks, virtually all CTG records demonstrate episodes of high variation, while approximately three quarters of records will also possess episodes of low variation.[54] Neither the incidence of low variation episodes or proportion of time they occupy in the record appears to change with gestational age. Only the mean duration of low variation episodes increases with gestational age while heart rate variation decreases. Near-term episodes of low variation are believed to represent quiet sleep.[2,59] This is due to quiet sleep being

consistently identified in preterm newborns after 36 weeks gestation.[66] The most clinically useful sign of a deteriorating fetus between 24 and 38 weeks is the progressive reduction in FHR variation, especially when combined with declining fetal movements across successive records.

In computerized CTG, episodes of low and high variation are identified by first determining the minute-by-minute deviation of the signal from the baseline after areas of deceleration or signal loss exceeding 50% have been removed. Computerized CTG calculates the "minute range," which is the sum of the absolute values of the maximum deviation above and below the baseline in a given minute. If there are no deviations below the baseline, the minimum baseline value is used. LTV is the mean minute range for the entire recording: the average of consecutive minute ranges. An episode of low FHR variation is identified when 5 of 6 consecutive minute ranges fall below a threshold that would be equivalent to a pulse interval of 30 milliseconds.[62] Likewise, an episode of high variation can be identified as 5 of 6 consecutive minute ranges of at least 32 milliseconds.[62] Episodes of high variation are confirmed if the mean minute range for the entire episode is above the first centile for mean minute ranges for episodes of high variation at that gestational age. If a CTG recording contains an episode of high variation, it is deemed "reactive". This mean FHR is observed to decrease between 24 and 30 weeks gestation,[67] after which point it begins to increase until labor, while the heart rate solely within periods of low variation decreases.[62]

STV and LTV

STV is defined as the mean absolute difference in pulse intervals averaged over one minute; however, as this measurement is not possible with CTG, the differences between the average pulse interval for each epoch are averaged for each 1-minute interval and these averages are then averaged over the entire CTG recording to provide the STV in milliseconds. STV is an important metric because if a CTG does not demonstrate an episode of high variation, the STV value serves as a good predictor of metabolic acidaemia, intrauterine death, and worse postnatal outcomes.[68,69] Short and LTV also increase substantially between 20 and 40 weeks gestation while baseline variation plateaus at around 29 weeks.

Basal heart rate

In computerized CTG, the basal heart rate is determined as the average FHR during episodes of low FHR variation, the normal range for which is 116–160 bpm, with some exceptions. The basal FHR also decreases with gestational age.[56] Arrhythmias can cause bradycardias or tachycardias, however, fetal infection or maternal pyrexia are also known to cause the latter. A sustained bradycardia <105 bpm has been observed to precede intrauterine death and therefore warrants immediate further investigation.[48,70] Importantly, in the majority of at-risk fetuses, the basal heart rate is within the normal range.

Sinusoidal rhythms

A sinusoidal rhythm is a rare CTG pattern associated with fetal distress and poor outcomes. FIGO classifies a sinusoidal rhythm as a regular, smooth, undulating signal, resembling a sine wave, with an amplitude of 5–15 bpm, and a frequency of 3–5 cycles per minute. This pattern lasts more than 30 minutes, and coincides with absent accelerations.[71] Low frequency sinusoidal rhythms (0.2–0.5 Hz) in the presence of an otherwise flat recording indicate disease and a poor fetal outcome, whereas high-

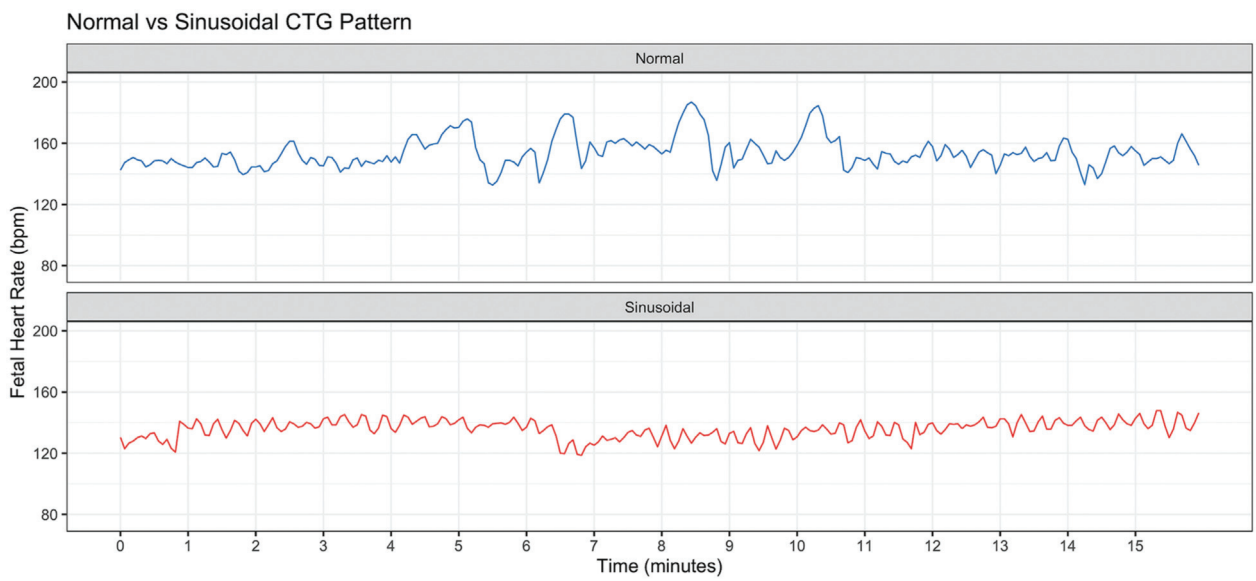

Figure 4. Comparison of a normal antepartum CTG pattern (blue) and a sinusoidal pattern (red) of two fetuses at 39 gestational weeks. The sinusoidal pattern is smooth, regular, and oscillates between 3 and 4 cycles (high frequency sinusoidal pattern) per minute with an amplitude between 5 and 15 bpm around the baseline heart rate. There is reduced baseline variability and no accelerations are present. This baby was acidaemic (pH = 7.07), had low Apgar scores, and required intubation. bpm: Beats per minute; CTG: Cardiotocography.

frequency (2–5 Hz) sinusoidal rhythms (Fig. 4) are associated with fetal anemia, fetal or maternal hemorrhage[28,72] or fetal intracranial hemorrhage. Because these events are exceedingly rare, it is difficult for a clinician to acquire enough experience recognizing them reliably. The DR computerized CTG analysis system for identifying sinusoidal rhythms was developed using 72,297 CTG traces and is capable of autonomously identifying these rhythms by modeling the effect sinusoidal rhythms have on the ratio of STV to LTV in the absence of episodes of high variability and alerts the operator to the potential presence of either a low- or high-frequency sinusoidal rhythm.[1,28]

Uterine contractions and fetal movements

Uterine contractions can be identified in computerized CTG when the tocodynamometer tracing exceeds its resting level by more than 16% for at least 30 seconds. Fetal movements are captured by a maternal handheld event marker and are not subject to computerized analysis beyond determining the average number of movements per hour alongside uterine contractions. Interestingly, besides a peak at 37 weeks, the mean number of fetal movements demonstrates no trend with gestational age. Fetal movements are reported to be ten times more frequent during episodes of high variation.

Computerized CTG in clinical practice

The primary role of computerized CTG in clinical practice is as a test of normality. The DR system utilizes ten criteria to establish normality, each of which were derived from over 48,000 CTG records and have been iteratively refined over the following 17 years, with the most recent iteration developed from >78,000 records. These criteria assess the episodes of high variation, STV and LTV, accelerations, decelerations, basal heart rate, fetal movements, signal quality, and whether a sinusoidal rhythm is present (Table 2). A randomized control trial testing the application of computerized CTG involving 2869 pregnant women concluded that computerized CTG resulted in improved record quality, a significant potential reduction in recording time, and demonstrated for the first time that the computerized system was better at estimating FHR variation due to human visual misinterpretation.[73] As such, the mean length of a recording that meets the DR criteria of normality is between 16 and 18 minutes, resulting in a significant reduction in recording durations for otherwise normal traces. Furthermore, the DR system provides a printed report of the analysis of the trace, detailing the results for each of the criteria in addition to the FHR trace, tocodynamometry, and fetal movements.

The DR system has been subjected to clinical validation. A study in which cordocentesis was performed immediately following DR CTG analysis demonstrated an LTV <20.0 ms (STV <3.6 ms) associated with severe fetal hypoxemia and acidaemia.[74] A comparative study between cord blood gas analysis results and DR analysis in babies born via elective cesarean section within 24 hours of recording demonstrated STV, LTV, and episodes of low variation are all related to umbilical artery pH, acidaemia, and hypoxemia.[49,75]

However, with the exception of the sinusoidal rhythm, the system is not recommended for use in diagnosis of specific fetal diseases. Moreover, a severely abnormal CTG does not require computerized analysis. As such, a "grey zone" of computerized CTG analysis exists. Traces that are not deemed "normal" by failing to meet the DR criteria are not necessarily immediately deemed "abnormal" and cannot be used to identify distinct pathologies. If the system fails to meet criteria after 60 minutes, analysis ceases, the report printed and a recommendation to seek clinical review is made. Importantly, computerized CTG analysis is a cross-section, or "snapshot", of the fetus at the time of recording and cannot, at present, provide predictive insights into the short- or long-term trajectory of the fetus.

There are currently no computerized CTG analysis systems that market themselves as devices for the diagnosis of disease states. Moreover, the absolute number of criteria that are met out of the ten possible criteria in the DR system are not to be relied upon as an

Table 2

The Oxford system's criteria for normality.

1. The recording must contain at least one episode of high variation.
2. The STV must be >3.0 ms, but if it is <4.5 ms the LTV averaged across all episodes of high variation must be >3rd percentile for gestational age.
3. There must be no evidence of a high-frequency sinusoidal rhythm.
4. There must be at least one acceleration, or a fetal movement rate ≥20 per hour and an LTV averaged across all episodes of high variation that is >10th percentile for gestational age.
5. There must be at least one fetal movement or three accelerations.
6. There must be no decelerations >20 lost beats if the recording is <30 minutes, no more than one deceleration of 21–100 lost beats if it is >30 minutes, and no decelerations at all >100 lost beats.
7. The basal heart rate must be 116–160 beats/min if the recording is <30 minutes.
8. The LTV must be within 3 standard deviations of its estimated value or (a) the STV must be >5.0 ms, (b) there must be an episode of high variation with ≥0.5 fetal movements per minute, (c) the basal heart rate must be ≥120 beats/min, and (d) the signal loss must be <30%.
9. The final epoch of the recording must not be part of a deceleration if the recording is <60 minutes or a deceleration at 60 minutes must not be >20 lost beats.
10. There must be no suspected artifacts at the end of the recording if the recording is <60 minutes.

bpm: Beats per minute; LTV: Long-term variation; STV: Short-term variation.

indicator of disease severity. For example, a trace meeting three out of ten criteria is not necessarily significantly three-fold worse than a trace meeting nine out of ten criteria. CTG features, such as episodes of high variation or accelerations can be absent in a CTG trace in completely normal fetuses. To assist the clinician in the assessment of traces failing to meet criteria, the DR system provides an output of the identified criteria at 60 minutes, as well as associated measurements, for example, STV. In these cases, observing the trends in the CTG for successive traces acquired throughout the pregnancy has been shown to provide useful insight, being most discernible when successive records demonstrate declining variation and declining fetal movements. Several of the DR criteria incorporate indicators of fetal distress and possible "terminal" traces. If these indicators are absent, for example, if very large decelerations are present, and criteria fail to be met due to this, then these decelerations can be used by the observer to assist in clinical decision making.

Computerized CTG has seen increased utility over the past decades as a clinical research tool.It has been employed in studies investigating longitudinal changes of biophysical profiles in fetal growth restriction,[76] the effect of different medical investigations, including the maternal glucose ingestion during the oral glucose tolerance test,[77,78] the safety of contrast-enhanced ultrasound with respect to uteroplacental circulation[79] and fetal magnetic resonance imaging.[80] In addition, it has been used to study the development of delivery planning protocols for fetuses with intrauterine growth restriction[81] and risk prediction of neonatal acidaemia at birth in combination with other investigations,[82] the effects of vibroacoustic stimulation on FHR in term fetuses,[83] prediction of acid-base status in placentalinsufficiency when combined with venous doppler investigation,[84] investigationofthe effect of pharmaceutical agents on FHR profiles,[85,86] the effect of maternal co-morbidities (eg, asthma) on FHR[87] and maternal race and ethnicity in FHR patterns,[88] to name a few.

Conclusion

The DR system of computerized CTG analysis has enabled the effective assessment of antepartum CTGs in a consistent and reliable format that significantly outperforms humans at determining whether a trace is normal. It substantially reduces the average recording duration required to make this assessment using fundamental signal processing algorithms, most importantly the ability to reliably fit a baseline to the CTG trace. This has facilitated the rapid identification of well-established patterns currently known to exist in CTGs, such as accelerations, decelerations, STV and LTV, and episodes of high and low variability. However, computerized CTG is not a universal panacea. A CTG that is not classified as "normal" is not therefore immediately "abnormal" and instead warrants further investigation by the observer. Computerized CTG is also unable to make future predictions regarding pregnancy outcomes and is unable to identify unique disease states. With the recent advancement in machine learning algorithms and hardware, especially neural networks employing deep learning methodologies, computerized CTG analysis is ripe for the development of advanced diagnostic models that are not only able to provide this same level of normality assessment but also potentially provide much richer insights into specific disease states of the fetus as well as its future.

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Conflicts of Interest

None.

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