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Opinion

Terminology of three-dimensional and four-dimensional ultrasound imaging of the fetal heart and other moving body parts

With the recent advent of high spatial and temporal resolution three-dimensional (3D) ultrasound, fetal moving anatomy, especially the heart, will become a major interest of clinical research and application. This Opinion discusses terms (Table 1) used (or misused, in the author's opinion) for describing various multi-dimensional imaging features, including '3D', 'four-dimensional (4D)', 'real time', 'cardiac gating', 'online' and 'offline'. Real-time imaging should only be used to indicate a system capable of displaying images (1) virtually as they are acquired, and (2) at about a cinematic rate (to 'fool' our visual perception). It should not be used (1) to describe systems only capable of displaying images with a certain delay after data acquisition, or (2) to imply whether or not the rate is sufficient to distinguish temporal events, such as rapid fetal cardiac phasic changes. I believe the terms 'direct' and 'indirect' volume scans should be introduced (Table 1) to describe whether a volume can or cannot be scanned within a time sufficiently short that movement is negligible, emphasizing the relativity in speed between 3D scanning and target motion.

With conventional, slice-reconstruction 3D approaches, data are acquired using an imaging plane scanning over a volume of interest (VOI). The 3D scanning needs to cope with three situations in terms of VOI motion. First, if the VOI is an immobile target, such as a stationary fetal face, only spatial tracking of the imaging plane movement is necessary for correct reconstruction of the acquired slices into 3D images. Second, if the VOI is a target in regular motion (such as the heart), temporal tracking must also be done to allow the slices to be reconstructed not just correctly in 3D spatial dimensions but also correctly in the fourth, temporal dimension (cardiac cycle). In pediatric and adult studies, electrocardiography, by means of cardiac gating, has successfully served this purpose. Unfortunately, it cannot be reliably used in fetal studies due to maternal and other interference. Third, if the VOI shows irregular motion (such as a random fetal smile) within the time constraint for scanning, there is no way to synchronize the movements with the slice-reconstruction approaches. The resulting 3D images will be degraded by motion artifacts (Figure 1).

Over the last several years, new methods and techniques have been developed in order to avoid image degradation caused by motion of the anatomy and to attain dynamic information arising from the motion. The most related developments are real-time 3D imaging[1–7], sonographic motion gating[8–15], and minimally compressive scanning[16,17].

Real-time 3D ultrasound makes it straightforward to comprehend some morphological dynamics, such as yawning, sucking, smiling, crying and blinking[1–4]. This offers a practical means for assessment of neurophysiological development, as well as for detection of anatomical pathology[18–20].

Ultrasonic cardiac gating can be performed offline[8,9] or online. Online gating can be achieved by pre-3D-acquisition heart-rate setting[10,11], by in-3D-acquisition (real-time) tracking[12,13] or by post-3D-acquisition correlation[14,15]. Cardiac cyclical information is extracted by M-mode, spectral Doppler or similar techniques from the fetal heart or arteries, allowing the removal of motion artifacts and the creation of dynamic 3D (or 4D) images of the *in-utero* heart. Preliminary gated and non-gated studies have shown the potential of 3D for depiction of complex normal/abnormal cardiac structures (Figure 2)[12,21,22] and intracardiac flow[22,23], for exclusion (including tele-screening) of major congenital cardiac defects[11,15,24–27], for estimation of overall heart volume[28] or stroke volume[29], and for detection of fetal arrhythmias[30,31]. With the use of real-time 3D ultrasound, 4D cardiac data can now be acquired more easily, sometimes without the need for cardiac gating[5–7]. The latest progress in matrix transducer technology will see all future 4D acquisitions being carried out with real-time 3D systems, and with real-time gating when necessary[32,33].

Based on our experience, together with a review of related (English) literature, this Opinion attempts to discuss and define the above terms. Although theoretical, this discussion may be of help for objective selection of competent 3D systems for specific scientific and clinical applications.

DIMENSIONALITY IN MEDICAL IMAGING

Three and four dimensions

When time is treated as a dimension, a two-dimensional (2D) display can mean either a display with one temporal and one spatial dimension (such as M-mode waveforms) or a display with two spatial dimensions (as seen in early, static cross-sectional ultrasound). Similarly, a 3D display can mean either a display

Table 1 Summary of proposed terms for multi-dimensional imaging of moving structures

Proposed term	*Definition*	*Comments*
Dimensionality	Three-dimensional (3D) should refer only to spatial dimensions while four-dimensional (4D) to three spatial dimensions plus temporal dimension	More or subordinate dimensions may be required for complete understanding and analysis of other properties obtainable by advanced imaging
Real time	Negligible delay between acquisition and display; images updated at least as quickly as visual persistence	Observer-dependent term; may be inadequate for clinical application where human eye/brain is a limiting factor
Direct or indirect volume scanning	Direct volume: scanned i) in totality ii) within a time in which movement is negligible iii) with sufficient spatial resolution; Indirect volume: if any of the conditions for direct volume are not met	Object-dependent term addressing relativity between scanning speed and target motion; application-specific – imaging rapidly moving structures may require acquisition rates much higher than real-time rate
Online or offline	Online: acquisition, processing and display sufficiently rapid for analysis during the patient scan (within seconds or a few min); Offline: processing and display which take longer such that they cannot be completed during or immediately after the scan	Online includes real time but need not be real time.

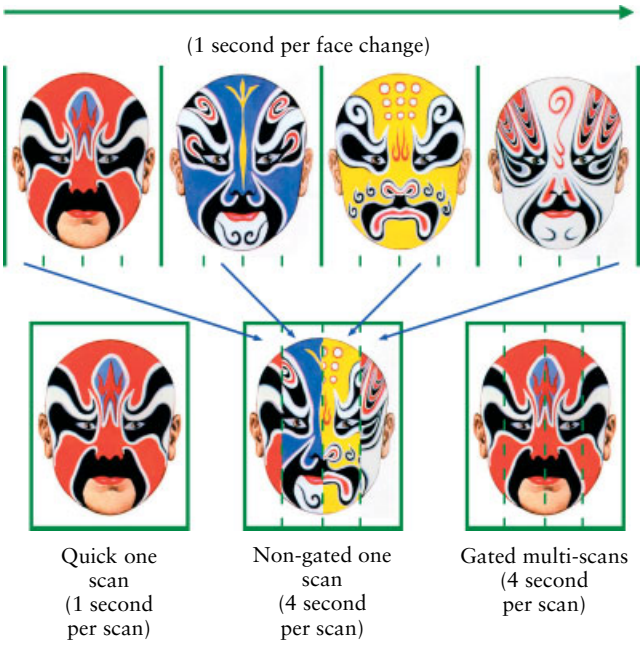


Figure 1 Target speed, scanning speed, motion artifact and motion gating. Some Chinese opera actors are very skilled at changing faces – altering facial masks in a blink. Imagine an actor can change one face per second and cyclically makes four changes (upper panel). If a camera scans the actor's head from the reader's left to right, and the scanning speed is 1 s per head-width, it is possible (though not necessary) for every scan to capture an entire face (lower panel, left). If the scanning speed is 4 s per head-width, one scan can only capture one quarter of each of the four faces, e.g. the 1st, 2nd, 3rd and 4th quarters of the four faces, respectively (lower panel, middle), causing distortion (motion artifact) in the resulting photograph. However, a 4-s scan can be synchronized (gated) with the face changing, say, starting the first scan with the red-cheeked face through to the white-cheeked face, then moving the camera right for a quarter of a head-width and repeating the scan, and repeating this process twice more. Four non-distorted faces can then be reconstructed; shown here is only the red-cheeked face (lower panel, right) from the 1st, 2nd, 3rd and 4th quarters of the 1st, 2nd, 3rd and 4th scans, respectively. This gating principle for the actor changing faces applies similarly in cardiac gating as the heart changes phases. (Peking Opera face paintings by M.L. Zhao, courtesy of http://www.jingjuok.com).

with one temporal and two spatial dimensions (as seen in real-time cross-sectional ultrasound) or a display with three structural dimensions (as seen in static 3D ultrasound). To avoid such confusion, it is advisable to restrict the use of 'dimension(s)'/'dimensional' to indicate only spatial dimension(s) while using 'time'/'temporal', 'motion'/'moving', or 'dynamics'/'dynamic' to indicate the temporal dimension. An exception can be made in the case of 4D which can be unmistakably used to indicate the three spatial dimensions plus the temporal dimension.

More and subordinate dimensions

4D imaging is a simple description of space and time which most of us can comprehend without any difficulty. To facilitate re-creation of a virtual functioning anatomy for detailed analysis, it is sometimes necessary to treat as additional dimensions some distinct biophysical or biochemical properties, such as the heart sounds, myocardial kinetics, intracardiac hemodynamics and oxygenated hemoglobin saturation. It may also be necessary to divide one primary dimension into several secondary dimensions. For example, the temporal dimension should be further split into maternal and fetal cardiac cyclical dimensions when the placental circulation is studied.

'REAL-TIME'NESS

Current usage

Several terms have been used to describe high volume-rate scanning for 3D/4D imaging (note, the term 'frame rate' used in cross-sectional imaging should be replaced with 'volume rate' in 3D imaging). The most commonly used (and probably the most attractive) term is 'real time', such as in 'real-time 3D', 'real-time 4D', and 'real-time volumetric' imaging. These catchphrases are usually introduced by manufacturers for commercial promotion, but the actual volume rates to which they refer vary greatly (*c.* 8–24 Hz).

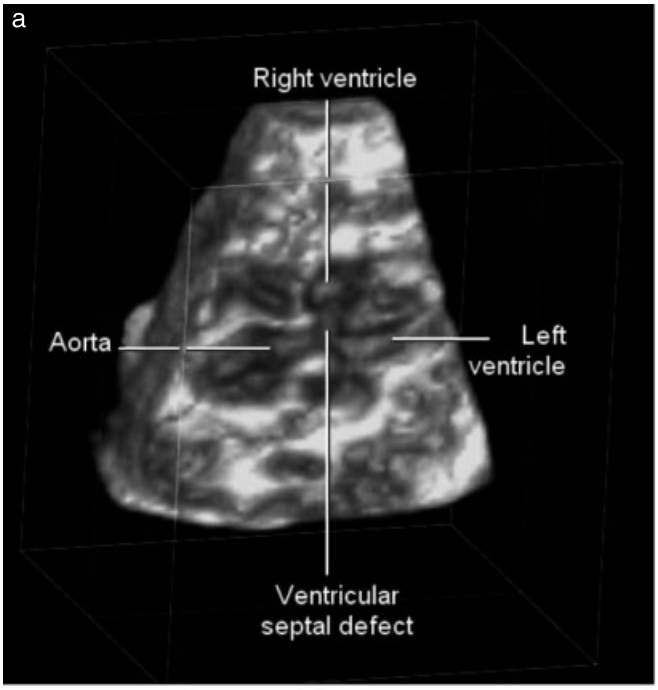
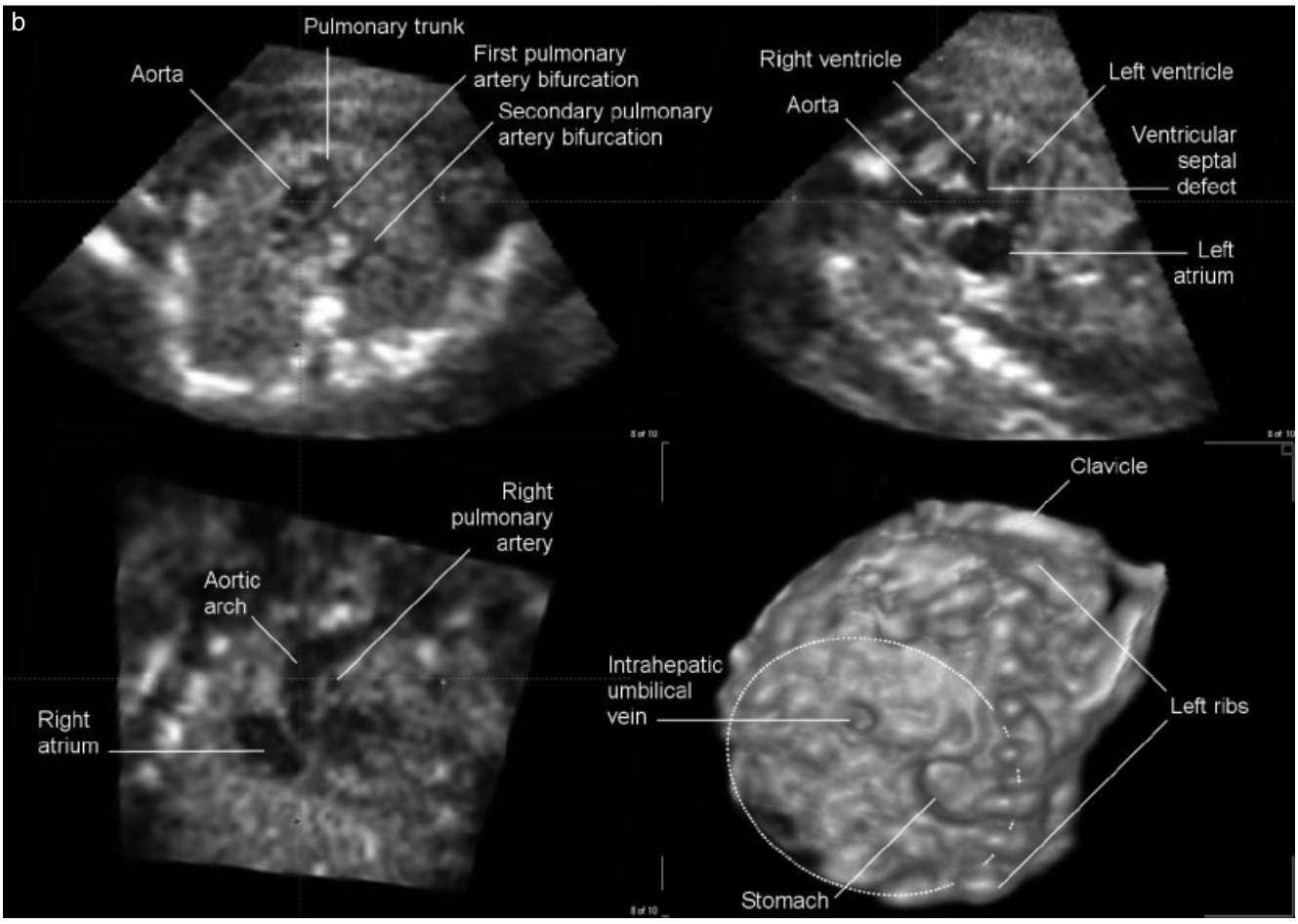


Figure 2 Four-dimensional (4D) ultrasound imaging of a 21-week-old fetal heart in part and in totality. (a) Real-time three-dimensional (3D) surface display of the open heart revealed a ventricular septal defect during a 'Live 3D' scan (using Philips Sonos7500, Philips). (b) The whole chest and upper abdomen were also acquired by four gated imaging volumes. Three imaging planes, reformatted offline using 4D CardioView (TomTec, Munich, Germany), demonstrated simultaneously all three features required for confirmative diagnosis of fetal tetralogy of Fallot: the ventricular septal defect, the overriding aorta and the narrowed pulmonary trunk. The detailed visualization of the entire course of the pulmonary artery and branches (including the secondary branches) is very important for helping parental counseling and surgical planning. (Movies can be found under the Fetal Heart entry on http://www.medphys.ucl.ac.uk/mgi/jdeng).



Proposed definition

According to the Oxford dictionary, 'real time' means the actual time during which a process or event occurs, especially one analyzed by a computer, in contrast to subsequent time when, for example, computer processing may be done or a recording may be replayed.

In sonography, the term should be used to indicate a system's ability to display dynamic morphology or morphological dynamics as the anatomical data are being

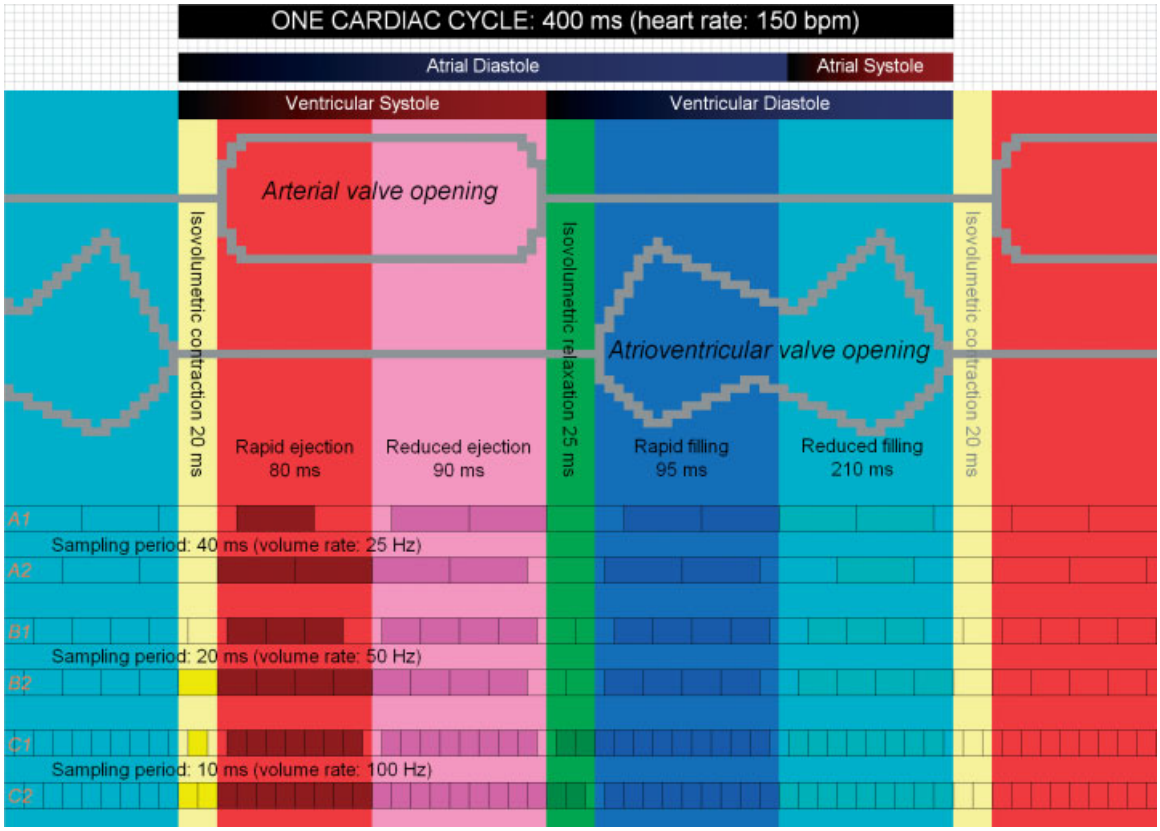


Figure 3 Schematic estimation of sufficiency of various temporal resolutions for distinguishing dynamic events of different time scales. At a 25-Hz volume rate, each of the four long (but not the two short, isovolumetric) cardiac phases can be fully sampled (darker blocks on each color column) at least once and most likely twice (*A1, A2*), making systole and diastole distinguishable during imaging. At 50 Hz, the short phases may (*B*2 during isovolumetric contraction) or may not (*B*1, and *B*2 during isovolumetric relaxation) be fully sampled once, resulting in the phases not always being recognizable in the images. At 100 Hz, these short phases can be fully sampled at least once and maximally twice, allowing their existence to be identified during a cardiac cycle. However, the accuracy for measuring the isovolumetric contraction time will only be about 50% at this rate. Note the time delay between the atrial and ventricular systole and diastole in the bars across the top, indicating potential pitfalls of using systolic peaks for gating the whole heart.

acquired, or with a negligible delay (a fraction of a second) between acquisition and visualization. It should also imply that 2D imaging frames or 3D imaging volumes can be updated within an interval equal to or shorter than the persistence of vision (or 'impression').

Key points

It is generally stated that the human eye and brain retain a visual impression for about one 10th to one 30th of a second (equivalent to a frame or volume rate of 10–30 Hz). The exact time depends on the brightness of the image and perhaps individual variation, but most people would probably agree that a rate less than 10 Hz will certainly produce 'jerky' movies. Strictly speaking, therefore, a 3D ultrasound machine incapable of a volume rate at or above 10 Hz should not qualify as a real-time imaging system.

Another point is that the threshold values for visual persistence are based on human tests (although traditional explanations for this phenomenon and the preciseness of the term itself have been challenged[34]). Consider an eagle flying high in the sky and at high speed, chasing a rabbit running rapidly on the ground; the predator must have much shorter (finer) persistence to be able to catch its prey. Hence, it is conceivable that persistence is species-dependent.

When talking about real-time imaging, we are actually talking about whether an imaging system is capable of achieving the visual continuity to satisfy the human eye/brain. Therefore, 'real time' is an observer-dependent, subjective concept; it does not necessarily reflect whether a frame or volume rate is adequate for visualizing the dynamics of an object for specific scientific or clinical purposes (Figure 3).

DIRECT AND INDIRECT VOLUME SCANNING

Current need

In medical imaging, what matters is the ability to distinguish and analyze an anatomy's dynamic events, rather than to see it moving continuously in our mind. Hence, there is a need for introducing objective terms to describe whether a scanning system is capable of achieving this.

Proposed terms

A 'direct volume scan' refers to any volume scan in which a VOI is scanned (1) in totality, (2) in an instant, and (3) with sufficient spatial resolution. An instant is defined here as a time so short that during this period the spatial movement of interest of the target and/or its components is negligible. If any of the three conditions is not met, a volume scan is considered an 'indirect volume scan'.

In contrast to real time, the two new terms are object-dependent concepts. The differentiation between direct and indirect volume scanning depends on the relativity between the speed of volume scanning and that of target motion (Table 2), or, by analogy, the relativity between the camera shutter speed and the face changing speed (Figure 1).

Key points

The importance of establishing whether a volume scan is indirect or direct is to help the operator determine whether or not spatial and temporal tracking are necessary when performing the scan. There are several aspects to be considered.

Built-in, spatial and temporal registration of 4D data

As illustrated in Table 2, a direct volume scan can be completed even with a slice-reconstruction 3D approach, if a VOI stays immobile during the entire acquisition. However, it is hard to find consistently stationary VOIs *in-utero* due to unwanted patient movements (e.g. fetal activity, maternal respiration) and/or environmental movements (e.g. probe-movement-induced abdominal deformation when using conventional approaches).

Real-time 3D systems can acquire a volume dataset without manual movement of the transducer. This is achieved by using a built-in mechanism for registering spatial and temporal information during a volume scan. Example systems include Philips Live 3D (based on matrix-array transducer technology[33,35,36], and Kretz Combison 730 (based on rapidly oscillating cross-sectional transducer technology[4,14,15,18]). If, and only if, one or more of the following requirements are also met, a real-time 3D scan can be regarded as a direct scan, and no additional spatial and temporal tracking are necessary.

Sufficient temporal resolution for the time scale of interest

In terms of cardiac 3D imaging, using a slice-reconstruction approach is certainly indirect volume scanning, but using a real-time approach may be either indirect or direct volume scanning (Table 2).

For general analysis of dynamic morphology of the fetal heart, we propose using a minimum volume rate of about 25 Hz (equivalent to a maximum of 40 ms for each imaging volume sampling period) as the cut-off point between direct and indirect volume scanning. This is because, except for isovolumetric contraction/relaxation, other cardiac phases each last longer than 80 ms (rounded numbers are used in this discussion for mathematical simplicity), and can be fully sampled at least once in one imaging volume per cardiac cycle (Figure 3).

However, the cut-off point between direct and indirect volume scanning will be affected by the different temporal resolutions required. If, for example, the aim of assessment is the global, 'intrinsic' myocardial contractility, then the time of interest will be scaled down to the shortest phase, isovolumetric contraction, of only 20 ms. It is impossible for a 25-Hz volume rate (40-ms sampling period) to distinguish this phase from others (Figure 3; more in 'A time point is shorter than a cardiac phase', below), thus the volume scanning is indirect. In other words, so-called real-time imaging does not necessarily mean that imaging of all dynamic details is possible. A 50-Hz (20-ms) scan is only capable of capturing the phase maximally in one imaging volume per cycle, with no accuracy in measuring the phase interval. To achieve 90% accuracy for the measurement, a 500-Hz volume rate may be necessary. This is far beyond the capability of any of the real-time 3D systems, which are still struggling to achieve a 50-Hz volume rate. Therefore none of the existing systems can be regarded as being capable of direct volume scanning for analyzing this important phase, although 2D tissue Doppler imaging of around 500 Hz may be able to assess the 'intrinsic' contractility of a much smaller region.

Table 2 Summary of relativity between direct and indirect volume scanning when using different 3D approaches and with different temporal resolutions*

Example volume of interest	*Three-dimenisional approaches*	*Direct or indirect volume scans*	*Temporal tracking*
Stationary face	Slice-reconstruction	Direct	Unnecessary
Slow-moving face	Slice-reconstruction	Indirect	Necessary
Slow-moving face	Real time (*c.* 25 Hz)	Direct	Unnecessary
Cardiac morphology and function	Slice-reconstruction	Indirect	Necessary
General fetal cardiac morphology and function	Real time (*c.* 25 Hz)	Direct	Unnecessary
Detailed cardiac function	Real time (≥50 Hz)	Direct or indirect, depending on the time scale of interest	Unnecessary or necessary

*Providing adequate spatial resolution and volume of interest coverage achieved.

Sufficient spatial resolution for the structural scale of interest

The cardiac structures can be divided approximately into major and minor scales. The former includes the four chambers, great vessel lumens and ventricular walls; the latter includes the valves, trabecular and papillary muscles and thin parts of septa.

When operating a 4D system to its utmost capacity, giving priority to one of the three fundamental parameters (imaging volume size, volume rate (i.e. temporal resolution) and spatial resolution) has to be at the expense of at least one of the other parameters. Therefore, when an increased volume rate becomes hypothetically sufficient to distinguish a phase, attention should be paid to whether the scanning can still resolve the structural details by which a phase is physiologically and morphologically defined. The isovolumetric contraction is defined as the interval between the atrioventricular valve closing and the arterial valve opening (Figure 3). A so-called direct volume scan must also be able to visualize reliably the closure and opening. This was impossible for prototype real-time 3D systems which could only recognize major fetal cardiac structures[5–7], but the latest real-time 3D systems can now offer much better spatial resolution and depict many minor structures (Figure 2)[33].

Inseparable entirety of the volume of interest

For a volume scan to be deemed as being direct, another key point is whether an inseparable VOI can be acquired within a time constraint such as a cardiac cycle without moving the transducer. By 'inseparable' we are referring to the fact that, if separated, certain assessments cannot be achieved without additional spatial and temporal tracking. Taking stroke-volume measurement as an example, the physiological definition requires measuring the volumetric changes of the whole ventricular chamber(s) between end-diastole and end-systole. If a real-time imaging volume is unable to cover the ventricles in their entirety, the acquisition should not be classified as direct volume scanning. In order to obtain the entire VOI, the transducer has to be moved. However, as soon as the transducer is moved during a 4D scan, spatial tracking and cardiac gating become essential. This requirement is independent of whether a cross-sectional or a volumetric transducer is used[5,12].

It needs to be pointed out that, if the objective of a study is not to quantify stroke volume but to assess qualitatively a cardiac structure, say the left ventricle, it is possible to assess it separately in several imaging volumes. Provided conditions discussed in the three previous key points are met, each separate scan can still be treated as a direct one. Without the need for gating in this assessment, direct scanning permits an operator to optimize 4D image quality during acquisition via imaging window and angle interaction.

The imaging entirety will primarily depend on the relationship between the size of a VOI and that of an imaging volume. In addition, other factors affect the entirety, subsequently determining the necessity of additional tracking. In prenatal studies, the main factors include fetal position and acoustic window, and the VOI distance from the probe and its alignment with the imaging volume. Because of the fully calcified chest bones (and liquid-filled lungs), 4D acquisitions of the heart often have to (and can) be made portion by portion through different imaging windows to avoid shadowing[5]. Because almost all existing real-time 3D systems form an imaging volume with a smaller near field of view and a larger far field of view (Figure 2)[5,36,37], positioning the VOI in the far field of view will increase the opportunity of embracing the whole VOI.

Fortunately, most non-cardiac anatomies generally move more slowly compared with the heart, and the parts can be studied separately, making most 3D scans using real-time systems (especially when at $\geqslant$ 16-Hz) fall into the category of direct volume scan. It is usually unnecessary to perform any additional tracking.

ONLINE AND OFFLINE

Current usage

Before acquired data can be visualized in 3D (using multiplanar reformatted 2D, and/or surface- or volume-rendered 3D displays), some postprocessing has to be carried out, taking time on computer system(s). Computing terms 'online' and 'offline' are often used to indicate, respectively, postprocessing and visualization performed on the same acquisition system that acquires the data, and those performed on a separate system after data transfer.

Proposed definitions

Online

'Online' means that necessary procedure(s), for example, motion gating, can be carried out rapidly (but not necessarily in real time) so that resulting 3D images can be displayed in real time or immediately after an acquisition, usually by/on the same system.

Offline

'Offline' denotes that necessary procedure(s) are carried out, or resulting 3D images are displayed, several minutes or even hours after an acquisition, usually by/on another system.

Key points

As networked, multi-system data acquisition, processing and visualization are now commonplace, the physical boundary between online and offline have become hazy, and the corresponding definitions should no longer overemphasize this boundary. The new definitions here

place emphasis on how fast a system (or a set of networked systems) is capable of producing clinical information in relationship to a particular patient scan. Online implies such a short (processing) time (usually not more than a few seconds or maximally a few minutes) that the patient can still be kept on the scanning table. Thereafter, if further acquisitions are indicated by the online results, they can be performed without recalling the patient. Offline implies such a long (processing) time (usually several minutes or even hours) that the patient may have to be sent away after a scan. If further acquisitions are necessary, the patient has to be rebooked.

POTENTIAL MISUSE AND MISUNDERSTANDING OF THE TERMS

Temporal tracking (gating) is unnecessary when using real-time 3D imaging

This depends on the particular circumstances. If a real-time imaging system is unable to scan an entire VOI with required temporal and spatial resolution (see key points in 'Direct and indirect volume scanning' above and Table 2), the scanning is indirect, and temporal tracking is necessary.

Gated 3D imaging can be called dynamic 3D (or 4D) imaging

Again, this depends on the circumstances. If a 3D scan is only gated at one time point (e.g., end-systole) and one slice is acquired per cycle, only one static 3D image can be produced. Gated imaging is time-point specific, but not necessarily dynamic, imaging.

Cardiac wall waveforms all peak at consistent time points throughout cardiac cycles

This is not true when imaging a large portion of the heart. Some gating methods involve the use of M-mode waveforms (such as the incursion peaks) to determine the consistent time points (such as end-systole) of each frame. However, to allow such correlation to work accurately, one of two related prerequisites must be met.

Firstly, the heart rate must be consistent during a slice-reconstruction scan, which usually takes about 10–30 s. Unfortunately, fetal heart rate fluctuation is common even under physiological conditions. Secondly, various structures must contract/relax in a similar pattern during phasic changes to allow identification of consistent time points. This is impossible for the whole heart. For example, the maximum incursion of most ventricular walls forms systolic peaks, but the atria only contract during ventricular diastole (Figure 3), albeit forming similar peaks. In fact, even different parts of the ventricles do not start contraction and/or relaxation at exactly the same time.

Cardiovascular Doppler tracing accurately reflects cardiac cyclical changes

This is not always true. Some gating methods involve the use of an extra, spectral Doppler transducer or cardiotocograph to trace cardiovascular waveforms (such as the umbilical arterial ones), in addition to a primary, real-time 2D or 3D transducer for acquiring structural volume data[13,38]. Because the waveforms are generally synchronized with cardiac cycles, they can be used for real-time gating. However, a cardiac pulse takes time to travel to an arterial site; a time point (say, end-diastole) on the umbilical tracing then occurs later than the corresponding point on the aortic tracing. If the heart rate and other hemodynamic parameters vary substantially from one cycle to another during a 4D scan, the time delay may no longer be consistent and may become a source of error[12].

Online gating is real-time gating

Real-time gating must be online gating; online gating may be real-time gating, but not necessarily. Online includes real time but need not be real time. This is because some gating methods only record temporal information simultaneously with structural data acquisition but without direct control on when the data should be acquired. Gating is only performed on the acquired data (immediately) after acquisition online or even offline (see the introduction to this Opinion).

Real-time gating is necessarily better than other online and offline gating

This depends on whether the gating signals are intrinsic and reliable. External signals, either based on the cardiac cycle determined before an actual 4D acquisition or artificially estimated, have been used for gating. The problem is that, between the pre-acquisition time and in-acquisition time, the fetal heart rate may change substantially, making the method depend on luck. Intrinsic signals, i.e. those from the cardiovascular system during the time of structural data acquisition, would normally be more reliable whether they are used for online (including real-time), or offline gating.

A time point is shorter than a cardiac phase

There are several significant periods in a cardiac cycle, referred to as cardiac phases (Figure 3). In theory, a time point indicates a 'length-less' point in the cycle. During a real-time 3D scan, however, the length of a time point effectively equals 1000 ms divided by the volume rate, i.e. the time needed for forming one imaging volume – a volume sampling period. A 25-Hz volume rate is equal to a 40-ms sampling period, which is two times longer than a normal isovolumetric contraction (phase). Going back to the proposed definition for direct or indirect

volume scanning, very qualitative terminology can be mathematically expressed:

$$\begin{aligned}\text{Motion negligible} &= \text{shortest phase to be studied}\\ &\div \text{volume sampling period}\\ &\rightarrow \text{infinity}\\ \text{Motion not negligible} &= \text{shortest phase to be studied}\\ &\div \text{volume sampling period}\\ &= 20\text{ ms} \div 40\text{ ms}\\ &= 0.5 \neq \text{infinity}\end{aligned}$$

CONCLUSION

In this article, some 3D terms have been examined and redefined for theoretical correctness and consistency, and to provoke further discussion. While it is understandable for these terms to be cross-used (and even 'abused' for marketing purposes), their usage in scientific publications should be as definite as possible. In research reality and clinical practice, however, it is often the pursuit of approximation rather than perfection that matters more. Hence, whether a 3D technique is useful very much depends on whether it is able to extract expected anatomical and functional information from a VOI. With regard to 4D system selection, it may be advisable to weigh up imaging volume size, rate, spatial resolution and (3D and non-3D) functionalities available from a system against, correspondingly, the entirety, time scale, structural scale of a VOI and operational simplicity required by one's own research and clinical work.

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