CS-VIBE – a Breakthrough in Ultrafast Dynamic Breast MRI

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Abstract

In this article we present a compressed sensing (CS) – volume-interpolated breath-hold examination (VIBE) sequence[1] as a new approach for ultrafast dynamic breast MRI. Opposed to more common viewsharing techniques such as time resolved angiography with stochastic trajectories (TWIST), timepoints in CS-VIBE are independently obtained and therefore resolve the temporal blurring that is inherent to viewsharing techniques. The smart *k*-space filling of the CS-VIBE sequence allows for creation of high spatial resolution images from heavily undersampled data at an excellent temporal resolution of less than 5 seconds per volume obtained. As published previously [1] CS-VIBE allows acquisition of images at a similar quality as those obtained with TWIST at identical temporal resolution, but with a spatial resolution of 0.8 x 0.8 x 1.6 mm, thus more than halving the voxel size when compared to TWIST. This implies that CS-VIBE allows multiplanar reconstruction and assessment of morphologic lesion characteristics in multiple planes, which was so far not possible with viewsharing techniques.

Key points

- CS-VIBE allows ultrafast dynamic breast MRI at unprecedented spatial resolution
- CS-VIBE overcomes temporal blurring in ultrafast breast MRI
- Morphological lesion evaluation on CS-VIBE images is virtually identical to morphological lesion evaluation using conventional T1-weighted VIBE Dixon images

Background

Lately, interest in ultrafast dynamic breast MRI has surged. This is mainly due to the large improvements of MRI hardware and software that enabled the creation of high quality images at very high temporal resolution [2–5]. Already from studies in the early nineties it was evident that dynamic analysis of the inflow phase was more informative than late phase wash-out features [6]. However, initial approaches were single slice techniques and could therefore only be used to classify already known lesions at known locations. Around the shift of the century whole-breast acquisitions had become possible, albeit at spatial resolutions that still prevented most radiologists from actually looking at these images [7, 8]. Instead, the generated data was used for pharmacokinetic modeling using simple or more advanced iterations of the Tofts model [9, 10]. The thus obtained quantitative parameters were once again shown to yield more diagnostic information than wash-out features, and were complementary to morphologic assessment of lesion characteristics using the Breast Imaging Reporting and Data System (BIRADS) lexicon, or similar classification systems [7, 8, 11]. Especially K^{trans}, the transfer constant from the intravascular to the extravascular extracellular space proved to be a robust predictor of malignancy, being much higher in malignant than in benign lesions, which can be explained by the increased vascularization and the immaturity of these new-formed vessels in which the endothelial lining is often incomplete and sometimes even the basement membrane is lacking [12].

Nonetheless, the so-called 'quantitative' parameters still suffered from huge variation within patients and from site to site, mainly due to difficulties with the determination of a realistic arterial input function [13]. This is difficult due to the simple fact that in breast MRI no representative vessels that are large enough for measurements are present within the field-of-view. The common solution is to use a population based arterial input function, thus reducing the variation, but also the true quantitative aspect of the measurements. Alternative approaches make use of reference tissues, such as the pectoral muscle, but are likewise hampered by huge variations in the reference tissue due to the physical properties of the patients imaged [13, 14].

A further difficulty is that due to the limited spatial resolution maps of these pharmacokinetic parameters were not really sufficient for lesion detection, and use is therefore

[1] WIP. Cartesian CS-VIBE is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured. CS GRASP-VIBE is 510(k) pending and may be used for the same purpose.

still limited to classification of otherwise detected lesions (and possible evaluation of the effects of primary systemic therapies), although the prerequisite of knowledge of lesion location is lifted by the whole-breast approach [7, 8, 11].

This largely shifted when modern viewsharing sequences became available that improved spatial and temporal resolution well beyond the borders of what was obtainable with keyhole based techniques [2–5]. In fact, it became possible to generate images within 5 seconds that met the international standards for diagnostic breast MRI, with a spatial resolution in plane of 1 x 1 mm, and a slice thickness of only 2.5 mm [5]. Suddenly it thus became possible to actually detect lesions on ultrafast dynamic breast MRI and perform classification based upon dynamic and morphologic features using the same images. By generating temporal maximum intensity projections (MIP), it has become possible to create an actual movie of contrast inflow; in general first highlighting the most suspicious finding in the breast ('the light bulb effect'), as these tend to enhance fastest.

In addition, a strong simplification of the interpretation of the dynamic data obtained, abandoning the pharmacokinetic model, but just looking at the slope of the enhancement curve, allows for much broader use of the ultrafast dynamic data, hardly without loss of its classifying properties [5, 15]. The rule of thumb is simple; the steeper the curve, the more likely that a lesion is malignant. Hence the maximum slope (MS) is an excellent tool for lesion classification. Furthermore, in analogy to the previously mentioned light bulb effect, the earlier a lesion enhances relative to the enhancement of the descending aorta, the more likely that it is malignant. This is captured in the 'time to enhancement' (TTE) [16]. In general most malignant lesions enhance within 15 seconds after aortic enhancement, whereas benign lesions enhance commonly later.

The excellent classifying properties of these simple inflow dynamics have since been confirmed by several studies using both radiologists and machine learning techniques. In one of the largest series to date, comparing 217 cancers to 172 benign lesions, Dalmis et al. reported that the overall classifying property of the inflow enhancement curve was 0.84, which compares favorably to most morphologic characteristics [17]. Moreover, this was robust over all types of malignant breast lesions, with only a slightly lower performance in ductal carcinoma in situ (DCIS) (Table 1).

Cancer type	n	Classifying property of dynamic features
DCIS	38	0.7690 (0.6728–0.8469)
IDC	141	0.8459 (0.7969–0.8893)
ILC	38	0.8673 (0.8018–0.9161)

Table 1: Classifying capacity of inflow dynamics for different types of malignant lesions. *Adapted from Dalmis et al. [17].*

Screening and abbreviated MRI

In the era of preventive and personalized medicine, screening for disease that is better treatable in its asymptomatic form is becoming more and more important. This is particularly true for breast cancer, which has an excellent prognosis when detected early [18].

Due to the excellent sensitivity of breast MRI for cancer screening trials already commenced in the late nineties, mainly in women at increased risk. Recent studies repeatedly report a sensitivity of MRI of approximately 90%, more or less doubling the sensitivity of mammography in the same populations [19, 20]. Also a stage shift of detected breast cancers is observed, making them smaller and thus easier to treat when detected by MRI [21].

Nonetheless, MRI screening, although internationally supported for all women with a lifetime risk of more than 20–25% [22], is in many countries reserved for women with hereditary breast cancer susceptibility genes or a history of chest radiation during puberty. This is mainly due to the inherent high costs of breast MRI, that have even increased over recent years by our aim to improve the specificity of the technique by adding sequences such as T2, diffusion and even spectroscopy on top of the conventional T1-weighted dynamic contrast-enhanced series.

This has led to the recent introduction of abbreviated scan protocols, that are aimed at lesion detection only, and are not specifically tailored to obtaining the best possible classification of eventual lesions. In screening this seems more than acceptable, as by far most of the scans are normal.

The simplest form of an abbreviated protocol was presented by Kuhl et al. in 2011 and suggested acquisition of only two T1-weighted acquisitions; one before, and one after contrast administration [23]. This acquisition protocol takes about 3 minutes and hence largely reduces the scan time needed for breast MRI that is in most practices at least a quarter of an hour. Subsequent generation of subtraction images and MIPs allowed for fast and accurate evaluation of the MRI acquisitions and did not reduce either sensitivity or specificity when compared to a full diagnostic protocol.

However, especially in screening women at somewhat increased risk morphological features of cancers can sometimes be deceptively benign. Hence abandoning all dynamic information on top of the lack of T2 and diffusion-weighted imaging (DWI) is unwanted if it is not really necessary.

Ultrafast breast MRI performed during and shortly after contrast examination might be used to overcome this issue. In women without lesions it is obviously unnecessary, but since it can be obtained without lengthening the protocol, it provides additional classification tools in women with breast lesions at no penalty in terms of acquisition time. In fact, when only ultrafast breast MRI is performed the acquisition time might be even further reduced to

approximately 2 minutes [5]. In a study presented by van Zelst et al. seven readers read 200 cases containing 31 MRI screen detected breast lesions and 54 biopsied benign lesions using only ultrafast breast MRI (TWIST) and using a full diagnostic protocol (FDP) consisting of high-resolution T1-weighted acquisitions before and after contrast administration, T2, and DWI [24]. Overall, sensitivity between the two techniques was equal (84%, vs 86%, ns.), whereas specificity was in fact higher using only TWIST than the FDP (81% vs 76%, p<0.001). This unambiguously shows that ultrafast breast MRI has high potential as screening technique.

Still, rather than choosing either the simple abbreviated approach or the ultrafast approach it is possible to combine the techniques in a short hybrid protocol, interleaving a number of ultrafast acquisitions in between the two high-resolution T1-weighted series during contrast administration, without lengthening the acquisition time of the simple approach. Such a hybrid protocol allows for very fast and simple evaluation in women without breast lesions, but enables both morphologic assessment and dynamic analysis of the contrast inflow in women with abnormalities.

Compressed sensing VIBE

The rationale for a hybrid protocol implies that there are still shortcomings of the current ultrafast techniques available. These are present both in the spatial and the temporal domain. In terms of spatial resolution TWIST might achieve a diagnostic level according to international standards; but the slice thickness of 2.5 mm still limits the possibility of multiplanar reconstruction, and thus assessment of morphological features and lesion extent in other planes than the axial slices usually obtained. In terms of temporal resolution viewsharing inherently causes some temporal blurring and thus less reliable dynamic information, despite the successes that have been achieved so far.

	CS-VIBE
TR (ms)	4.47
TE (ms)	2.06
FA (°)	15
Field-of-view (mm²)	358.4 x 358.4
Matrix size	448 x 381
TWIST central region A (%) / Sampling density B (%)	-
Slice thickness (mm)	1.6
Voxel volume (mm³)	1.024
Phase resolution (%)	85
Slice resolution (%)	70
Acceleration factor	20
Acceleration mode	CS
Time resolution per volume (s)	4.55
Total acquisition time (min)	1:40

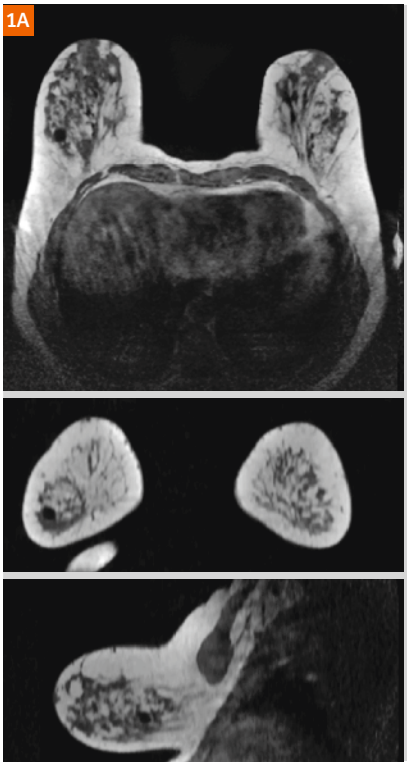
Table 2: Parameters of the prototype CS-VIBE sequence.[1]

By shifting the acquisition from a viewsharing approach to compressed sensing several of these limitations are overcome. CS VIBE incoherently subsamples the phase-encoding plane with variable density, obeying a Gaussian distribution in which the density is higher in the center of *k*-space than at its borders. Despite the sparsity of the sampling technique adequate images can be reconstructed by optimization of a cost-function. Since volumes are independently obtained per time point no temporal blurring is present. Furthermore, a spatial resolution is achieved of 0.8 x 0.8 x 1.6 mm. Parameters of the prototype CS-VIBE sequence are presented in Table 2.

In a reader study by Vreemann et al. presented at this years ISMRM [25], it was shown that image quality of the CS-VIBE is equal to that of TWIST, despite the fact that the voxel volumes are more than halved. Artifacts between sequences are somewhat different. TWIST is particularly known for infolding and ghosting artifacts, likely directly caused by the viewsharing; CS-VIBE seems somewhat more prone to pulsation artifacts from the heart, which are particularly seen in the axillary region. The image quality of CS-VIBE almost approaches that of the conventional VIBE Dixon acquisitions with a spatial resolution of 0.9 x 0.9 x 1 mm, acquired in 91 seconds (Fig. 1).

Morphological lesion evaluation based on the CS-VIBE was compared to evaluation of lesion morphology on VIBE Dixon and results were virtually identical, showing the excellent capability of morphological assessment on CS-VIBE acquisitions alone, which is enabled by the possibility to create multiplanar reconstructions of the acquired volume. In addition it becomes possible to create rotating MIPs; although these might not be very essential for diagnostic practice, they certainly improve the clarity of the scan when explaining the findings to treating physicians, in particular surgeons (Fig. 2).

Currently, the implementation of CS-VIBE in clinical practice is still somewhat limited by the required reconstruction time of approximately 45 minutes on the scanner. This implies that images cannot be generated during the daily program, but instead image generation has to be performed over night. While for screening this might not be a real problem, in the sense that there is in general no reason why scans could not be read one day after acquisition. However, it still prevents the technologists from controlling the quality of their work. Future advances in the calculating capacity of work-stations used for image generation will however likely resolve this issue.



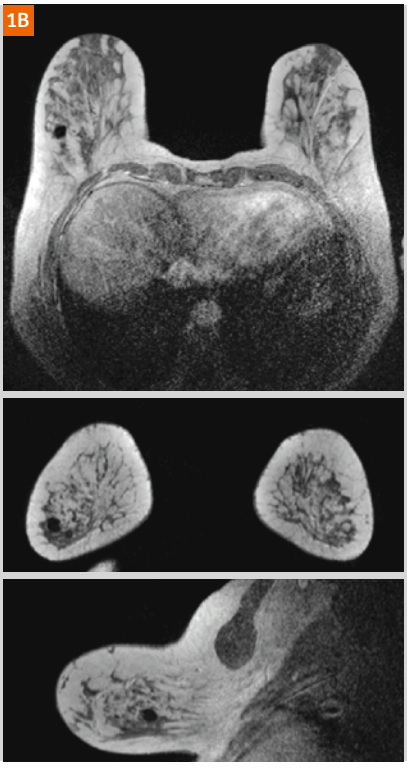


Figure 1: A comparison of image quality between the CS-VIBE **(1A)** and VIBE Dixon **(1B)** in multiple planes. Even though the VIBE Dixon acquisition is still somewhat sharper, morphological evaluation of structures within the breast is almost identical in all directions.

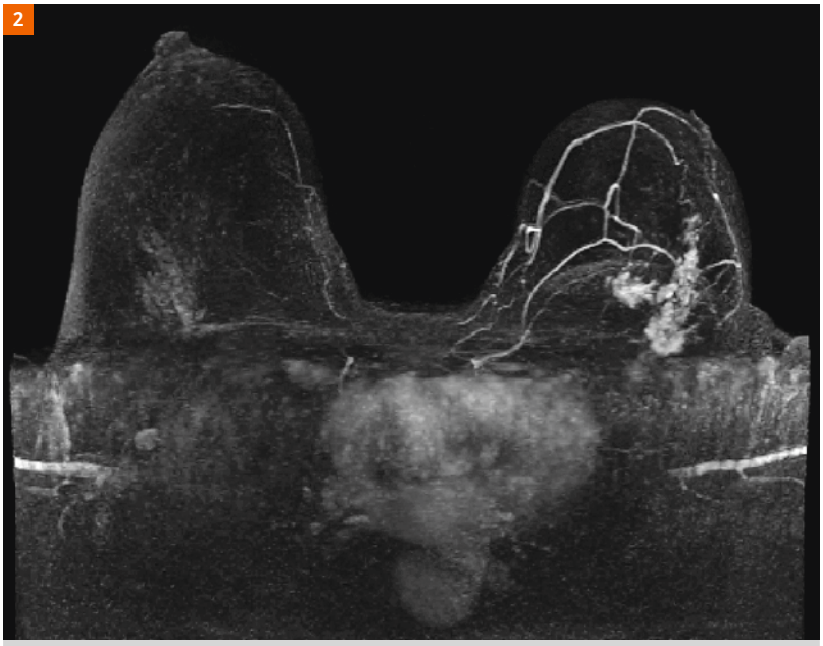


Figure 2: A maximum intensity projection image obtained from the first and last CS-VIBE acquisition, showing with high morphological detail a multifocal cancer in the left breast with marked vascular asymmetry.

In conclusion, CS-VIBE is a major step forward in ultrafast breast MRI; for the first time allowing high quality image generation at a spatial resolution that enables multiplanar reformatting, without temporal blurring and within 5 seconds. CS-VIBE therefore brings screening with ultrafast breast MRI alone one step closer.

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