Case study 2: Compressed SENSE in brain imaging on Philips Ingenia 1.5T (RA5.4)

Dr Rosa Sanchez Panchuelo, University Hospitals Birmingham Foundation Trust

Introduction

The Solihull Hospital, based at the centre of Solihull 8 miles southeast of Birmingham, is part of the University Birmingham Hospitals (UHB) NHS Foundation Trust. The MRI service at Solihull is a tertiary referral centre, hosting a 1.5 T Philips Ingenia MRI system. The 'brain tumour with contrast' protocol is used for diagnostic in suspected cases of brain tumours, treatment planning and longitudinal follow up. This protocol employs many 3D sequences. Hence, given that image compressibility is higher in 3D images (2 phase-encoding directions) compared to 2D images, the brain tumour protocol was identified as one that will better benefit from using CS.

The current appointment slot for patients undergoing this examination is currently 40 min long. We aim to accelerate the acquisition time significantly while preserving, if not improving, the image quality. As well as reducing the appointment time, we aim to improve patient comfort and reduce the number of repeated scans due to movement.

Methods- Staffing, Scanner and Sequence Information

The Philips compressed SENSE (CS) implementations combines compressed sensing and SENSE technique. Compressed SENSE is available on the Solihull 1.5 T Philips Ingenia system, which is on software version R5.4. The RF coil used was the dStream Head Coil, which includes the head coil and base (with the FlexCoverage Posterior spinal coil, integrated in the table, disengaged). Compressed SENSE is also available in four other scanners across the trust (one 1.5 T Ingenia at Good Hope Hospital, two 1.5 T Ingenia at the Heartlands Hospitals and one 1.5 T Ingenia Ambition at the Heartlands Treatment Centre) as well as in one 3 T Ingenia Elition at the Heartlands Treatment Centre.

The UHB NHS Foundation Trust has a dedicated Medical Physics MRI team supporting clinical work in all hospitals within the trust and other hospitals in the Birmingham area extending to Trusts in Somerset to North Wales. The support provided by MRI team includes sequence optimisation and development for specific MR applications. There is one MR physicist (70% FTE) who is leading in the implementation of advanced acceleration techniques across the sites supported by the MRI team and other hospitals across the Midland area. The superintendent radiographer at Solihull has a good knowledge of MR physics and a very keen interest in MR sequence optimization, hence we chose to evaluate compressed SENSE acceleration technology at Solihull and transfer the sequences to all other 1.5 T Ingenia scanners across the trust once the protocol had been optimized.

Sequence optimization was led by the superintendent radiographer at Solihull who leased with radiologist to obtain feedback of the diagnostic quality of the images. Optimization was performed gradually in patients, gradually evaluating one sequence at a time against the original sequence to ensure the overall scanning time per patient was not significantly increased during the optimisation process. For sequences where the SENSE acceleration was simply replaced by CS, the CS factor was gradually increased if image quality was not degraded, and radiologist confirmed that they could provide a clinical diagnosis from the faster acquisitions. Whenever sequences were replaced by alternative sequences (e.g., MultiVANE by TSE), several patients were scanned using both the original and optimized sequence prior to decide whether the alternative sequence was of good enough quality to replace the original diagnostic sequence. This optimization process took between 2 and 3 months to complete the full protocol.

Results: Protocol Information and Scan Parameters

The original MRI Brain protocol with contrast is used for diagnostic in suspected cases of brain tumours, for treatment planning as well as for longitudinal follow up. The protocol starts with 3D T_1-weighted IR TFE and T_2-weighted 3D BrainVIEW FLAIR acquisitions acquired in sagittal orientations with 1 mm and 1.1 mm isotropic resolution respectively. These are followed by a Diffusion Weighed Imaging (DWI) protocol using single-shot multi-slice SE-EPI with a set of b-values = [0, 500, 1000] s/mm^2 , acquired with 1, 2 and 5 averages respectively. This acquisition comprises 28 axial slices with 1.5x1.5 mm^2 in-plane spatial resolution and 5 mm slice thickens. A fourth pre-contrast protocol, which is not always requested, consists of a 3D Susceptibility Weighted Imaging phase (SWIp) axial acquisition based on a T2*-weighted FFE sequence with four echoes at TEs = [12,23,34,45] ms. After contrast administration, the protocol includes a T_2-weighted MultiVANE acquisition followed by a repeat of the pre-contrast T_1-weighted 3D isotopic volume acquisition and a T_1-weighted multi-slice SE acquisition. Both post contrast 2D acquisition volumes consist of 4mm thick axial slices acquired with sub-millimetre in-plane resolution. Further acquisition details for these sequences are shown in table 1.

Sequence	FOV (mm^3)	Resolution (Acquired, mm^3)	SENSE factor (P, S)	TE($_1$) (ms)	TR/ TR_{3D} (ms)	Other Details	Acq. Time
T1W 3D IR TFE Sag	240x240x160	1.00x1.11x1.00	AP=1, RL=2	3.4	3000	TI=0.95s,TB=216	5:38
3D BrainView FLAIR Sag	240x240x165	1.10x1.10x1.10	AP=2.5, RL=2	301	4800	TI=1660ms,TB=160	5:41
DWI Axial	230x230x153	1.50x1.51x5.00	AP=2	76	4600	b=[0, 500, 1000]	1:50
3D SWIp Axial	230x186x144	0.85x0.85x2.00	RL=2, FH=1.3	12	52	4 TEs, □TE=11ms	5:51
Contrast Administration							
T2 Multi VANE XD Axial	230x230x158	0.60x0.60x4.00	AP/RL=1.5	102	4073	MV % = 325	3:48
T1W 3D IR TFE Sag	240x240x160	1.00x1.11x1.00	AP=1, RL=2	3.4	3000	TI=0.95s, TB=216	5:38
T1W SE Axial	230x181x149	0.75x0.80x4.00	None	15	450	2 packages	3:28

Table 1*: Sequence details for the original protocol. TF stands for to the Turbo factor (TFE/ TSE factor for TFE and TSE sequences respectively).*

The optimized protocol has been accelerated by employing Compressed SENSE (CS) in all of the acquisitions except for the DWI sequence, for which CS is not available (see table 2 for protocol details). The pre-contrast 3D volume acquisitions were accelerated by determining the CS factor which yielded equivalent image quality in terms of signal to noise ratio and spatial resolution than the original sequences. In the case of the two post-contrast protocols employing (multi-slice) 2D axial acquisitions, the protocols were replaced for alternative sequences. The T_2-weighted MultiVANE XD protocol was replaced by a TSE sequence so as to allow for a Cartesian readout which is compatible with CS, whereas several acquisitions were explored to replace the T_1-weighted axial SE acquisition (see Figure 1A, left image); The first option was to use the same protocol without altering the spatial resolution but applying CS (2.2), which needed 2 averages to preserve the SNR, yielding a similar acquisition time to the original (3:20) and similar image quality (Figure 1A, middle image). The second option was to use an alternative 3D TSE volume (BrainVIEW) while significantly increase the spatial resolution (0.9 mm isotropic) using CS-SENSE=6.5, but although this yielded a high-quality image (Figure 1B, left image) the acquisition time was longer (4:20). Finally, an alternative 3D gradient echo volume acquisition (3D IR TFE) was considered (Fig.3, right images), whereby the inversion time (TI) and shot interval (TR_{3D}) parameters were adjusted with respect to the pre-contrast T_1-weighted sagittal acquisition, where grey matter to white matter contrast is maximized, so as to provide a more similar contrast to the T_1 SE contrast across the brain. Although

this acquisition was only slightly faster (15%) than the original sequence, it provides better image quality by significantly increasing the spatial resolution, with a voxel volume reduced to one third of the volume in the original acquisition. The post contrast axial T1 SE protocol was hence replaced with an axial 3D IR TFE acquisition.

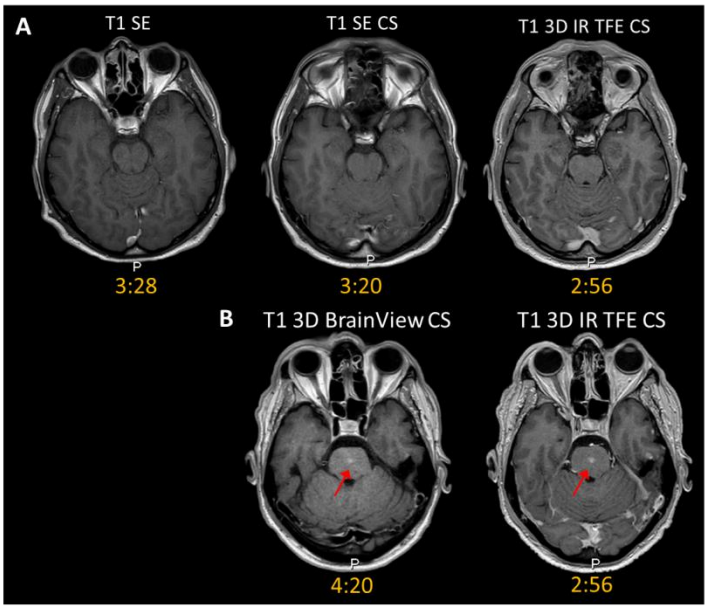

Figure 1: *Optimization of post contrast T_1-weighted axial acquisition. (A) Example slice acquired with original T1 SE protocol (left image) and equivalent T1 SE with CS (middle image), both acquired with 0.75x0.80 mm^2 in-plane resolution (0.45x0.45 mm^2 reconstructed), 4 mm slice thickness, compared to 3D IR TFE with CS (right image) acquired with higher resolution (0.9x0.9x0.98 mm^3, reconstructed to 0.48x0.48 mm^2 in-plane resolution). (B) Comparison of images acquired with 0.9 mm isotropic 3D BrainVIEW CS (left) and 3D IR TFE CS protocol (right). The 3D IR TFE CS images show similar contrast to the multi-slice SE and the 3D (TSE) BrainView, clearly showing the hyper intense lesion (red arrow) corresponding to melanoma metastasis on the patient on the bottom row.*

Sequence	FOV (mm^3)	Resolution (Acquired, mm^3)	CS factor, de-noising	$TE_{(1)}$ (ms)	TR/TR_{3D} (ms)	Other Details	Acq. Time
T1W 3D IR TFE Sag	230x230x176	1.05x1.05x1.05	2.8, default	3.4	7.5/3000	TI=0.95s, TF=208,	2:50
3D BrainView FLAIR Sag	230x230x176	1.15x1.15x1.15	6.5, default	301	4800	TI=1.66s,TF=160	3:55
DWI Axial	230x230x153	1.50x1.51x5.00	N/A	76	4600	b=[0, 500, 1000]	1:50
3D SWIp Axial	230x182x150	0.85x0.85x2.00	4, default	12	52	4 TEs, ΔTE=11ms	3:57
Contrast Administration							
T2 TSE Axial	230x185x158	0.60x0.65x.4.00	1.7, default	107	7736	TF=16	2:42
T1W 3D IR TFE Sag	230x230x176	0.90x0.90x0.98	2.5, default	4.6	9.4/2100	TI=1.05s, TF=213	2:56
T1W 3D IR TFE Axial	230x184x166	0.90x0.90x0.98	2.5, default	4.6	9.4/2100	TI=1.05s,TF=213	2:56

Table 2*: Sequence details for the accelerated protocol. TF stands for to the Turbo factor, corresponding to TFE and TSE factor for TFE and TSE sequences respectively. Notice the DWI sequence has not been modified.*

Figure 2 shows example images of the original protocol compared with the accelerated protocol. The acquisition times for each sequence are shown in yellow. Note that the SWIp acquisition is not always requested. Table 3 compares the acquisition times for each protocol and provides time savings across protocols. The total time for the exam card was about 31 minutes for the original protocol (25 minutes without the SWIp acquisition) and this was reduced to 21 minutes (17 minutes without the SWIp acquisition) with the AAT software.

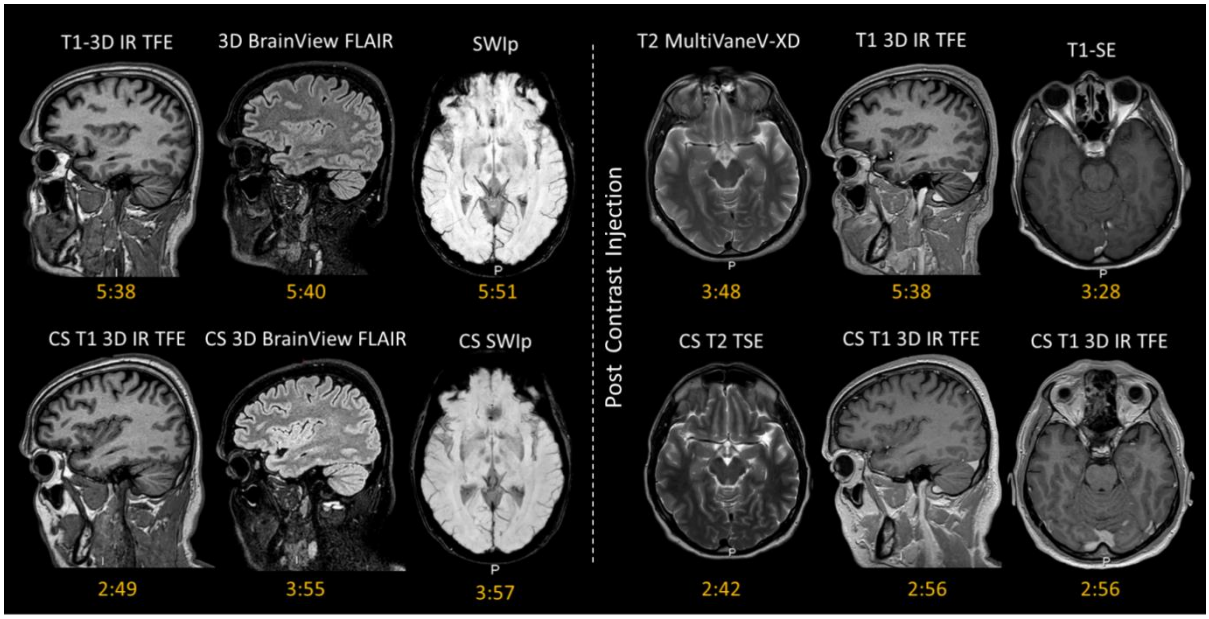

Figure 2: *Example images acquired with for the original protocol (top row) compared with those acquired with the accelerated protocol (bottom row). Acquisition times are quoted below the image in the yellow font. The spatial resolution of the acquisition was roughly preserved except for the post contrast T_1-weighted axial acquisition, which was increased by replacing the multi-slice SE acquisition by a 3D IR TFE sequence. The spatial resolution of the post-contrast 3D IR TFE sagittal acquisition was slightly improved with respect to the original acquisition.*

Sequence	Plane	Original	AAT (CS-SENSE)	Time Saved
T1W 3D IR TFE Sag	Sagittal	5:38	2:50	50%
3D BrainView FLAIR	Sagittal	5:41	3:55	31%
DWI	Axial	1:50	1:50	0%
3D SWIp	Axial	5:51	3:57	32%
Contrast Administration				
T2 Multi VANE XD	Axial	3:48	-	29%
T2 TSE		-	2:42	
T1W 3D IR TFE	Sagittal	5:38	2:56	48%
T1W SE Axial	Axial	3:28	-	15%
T1W 3D IR TFE		-	2:56	
Exam Card Total		31 min	21 min	32%

Table 3: *Summary of protocol time savings.*

Discussion

Compressed SENSE can effectively accelerate the acquisition protocols, if the original acquisitions we intend to accelerate are not limited by low SNR, particularly for 3D sequences where there are 2 phase-encoding dimensions that can be exploited in acceleration. Here, the pre-contrast T_1-weighted IR TFE sequence acquisition time was reduced by 50% by employing compressed SENSE. Note however, that the choice of CS factor directly impacts the acquired resolution of the image; here a CS factor of 2.8 provided 1.05 mm isotropic (acquired) resolution, yielding a voxel volume which is ~ 4% larger than the original acquisition. This is only slightly higher and hence acceptable; however, the spatial resolution of the acquired voxel needs to be careful monitored when modifying the CS factor to achieve the desire resolution. In practice this means that we are limited by the choice of CS factor we can use if we are to maintain the spatial resolution of the original sequence. Notice that certain factors may also improve the spatial resolution; by choosing a CS factor of 2.5 for

the post contrast acquisition T_1-weighted 3D IR TFE acquisitions, sub millimetre voxels (0.90x0.90x0.98mm^3) could be obtained yielding smaller voxels with only 71% of the original voxel volume. Therefore, provided SNR is high enough, compressed SENSE can also be employed to increase the spatial resolution and hence improve image quality while simultaneously reducing the acquisition time.

Here, the post contrast T_1-weighted 2D SE acquisition was replaced by a 3D IR TFE acquisition with improved image quality by providing higher resolution with nearly isotropic sub-millimetre voxels. The image contrast of the 3D IR TFE acquisition was matched to that of the 2D SE acquisition by employing a slightly longer inversion time (with slightly larger TFE factor) and shorter acquisition shot. Similarly, compressed SENSE can be applied to accelerate 3D T_2-weighted scans that would have been probability long otherwise; hence the larger benefit of CS in 3D imaging can be exploited to implement more high-resolution CS accelerated 3D acquisitions to potentially replace the standard thick slice 2D acquisitions in further protocols. In fact, all 2D FLAIR sequences in axial and coronal planes have now been replaced with 3D FLAIR with CS (with 2 mm slice thickness interpolated to 1 mm in all protocols across all Philip scanners within the trust, while the sagittal 3D FLAIR acquisitions for the tumour as well as the Multiple Sclerosis protocol have been replaced with faster acquisitions by using compressed SENSE.

Although the potential benefit of CS is greater for 3D sequences, 2D sequences can also benefit from compressed SENSE. Here, CS was applied to 2D TSE to provide alternative T_2-weigthed axial images with the same slice prescription and resolutions as the original Multi VANE XD acquisition, but at a fraction (71%) of the acquisition time. It is worth noting that like other advanced acceleration techniques, motion artefacts are enhanced in compressed SENSE acquisitions. However, the reduce acquisition times contribute to increase patient comfort and reduce the chance of motion. Although there are some image artefacts specific to compressed SENSE which the radiologist needs to be able to identify, such as the wax-layer artefact, the streaky-linear artefact or starry-sky artefact (see Sartoretti et al. 2018 for a review), in practice motion artefacts are the most prevalent artefact. The visual appearance of the motion artefact on brain images acquired with CS is comparable to that in images acquired without compressed SENSE (visible as semi-circular rings in in phase encoding direction), but the artefact was depicted in higher spatial frequency on images where CS is employed when there is head movement.

Conclusion

Overall, the total acquisition time for the examination was reduced from 31 min to 21 min. This has allowed to increase patient comfort as well as to reduce the allocated MRI appointment slot from 40 min to 30 min. The time saved has also allowed to run extra sequences or repeats without risk of running late.

References

Sartoretti T, Reischauer C, Sartoretti E, Binkert C, Najafi A, Sartoretti-Schefer S. *Common artefacts encountered on images acquired with combined compressed sensing and SENSE*. Insights into Imaging 2018, 9, pages 1107 – 1115.