INTRODUCTION: Time-resolved three-dimensional phase-contrast MRI (4D-flow) is a tool for imaging blood flow velocity profiles, but is limited in its clinical applications by its long scan time. In this study, we analyze the effect of the combination of a parallel imaging technique (GRAPPA) with an acquisition that removes the corners of k-space in order to further limit scan time. A previous study has shown that average velocity calculations are preserved when combining GRAPPA with the 4D-flow acquisition (1). We analyzed the effect on both mean velocity across the vessel lumen as well as the difference between individual velocity vectors (Figure 1), as individual vectors may effect calculations of wall shear stress and other variables that depend on the local velocity field (2).

MATERIALS AND METHODS: Time-resolved 3D PC MRI was used to assess neuro-vascular flow patterns in 3 patients at 1.5T and 3.0T (both scanners: Signa LX CNV, 12.0; GE Healthcare, Milwaukee, WI, USA), which has been previously described and validated (1, 3). High-performance gradient systems were used with a maximum gradient strength of 50 mT/m at 1.5T and 40 mT/m at 3.0T, and a maximum slew rate of 150 mT/m.s. An eight-channel head coil was used (MRI devices, Waukesha, WI, USA), and pulse oximetry was used for cardiac gating. The same parameters were used on both scanners: field of view 180 x 180 mm, 90% FOV, matrix size 300 x 180 x 30, TR/TE 5.46ms/2.12ms, flip angle 15°, venc = 100 cm/s, and receiver bandwidth of ±65 kHz. Frequency encoding was performed in the anterior-posterior direction. Three slice encodes were repeated in each RR interval, resulting in a temporal resolution of 65.5 msec. Therefore, 1,620 heartbeats were needed to acquire the data set (4 times PE 1,2 times PE 2, 1 times PE 3), for a total of 2,160 scans. As previously described, the six fully acquired data sets were subsampled using a variant of GRAPPA with outer reduction factors (ORFs) of 2 and 3 (1, 4). Additionally, the resulting 18 data sets were further subsampled by removing the data in the corners of the ky-kz plane and then zero-filling. The area of the remaining k-space data in this “cut-corner” acquisition is defined by the ellipse $\pi k_{\text{max}} k_{\text{max}}$ (5).

RESULTS: For ORFs of 2 and 3, the total number of heartbeats was reduced from 1,620 to 920 (a 43% reduction) and 700 (a 57% reduction). The cut-corner acquisition resulted in a further decrease to 1,222 (a 24% reduction from the fully acquired scan), 724 (a 21% reduction from the ORF 2 scan) and 559 (20% reduction from the ORF 3 scan). Differences in mean velocity measurements across the vessel lumen between subsampled data sets were clinically insignificant (all less than 3%). Figure 2 shows the effect on the mean percent difference between individual velocity vectors at each field strength with ORFs of 1, 2 and 3 as well as with and without the cut-corner acquisition. The mean difference between individual vectors was roughly ten times the difference across the fully acquired data sets. Additionally, the trend for higher reduction factors resulted in significant image and velocity degradation. The addition of a cut-corner acquisition to reduce scan time, we studied the effects of two k-space subsampling techniques on velocity data. As previously demonstrated, GRAPPA significantly reduces scan time, but at low field strengths, higher reduction factors result in significant image and velocity degradation. The addition of a cut-corner acquisition to GRAPPA resulted in minimal degradation of velocity data, while decreasing scan time by up to 25%. This can reduce the overall scan time from 20 minutes to 9 minutes when combining GRAPPA with an ORF of 2 and the cut-corner technique. We also have shown that as stochastic noise increases with k-space subsampling, there is preservation of mean velocity, but the error of individual velocity vectors increases. In clinical situations where calculation of mean or peak velocities is important, such as evaluation of arterial stenoses, k-space subsampling is inappropriate. However, in situations where the integrity of the local velocity field is needed, such as 4D visualization techniques like streamlines or calculation of wall shear stress, a full acquisition may be more appropriate.

CONCLUSION: A limitation of 4D-flow in the clinical setting is lengthy scan time. In an effort to reduce scan time, we studied the effects of two k-space subsampling techniques on velocity data. As previously demonstrated, GRAPPA significantly reduces scan time, but at low field strengths, higher reduction factors result in significant image and velocity degradation. The addition of a cut-corner acquisition to GRAPPA resulted in minimal degradation of velocity data, while decreasing scan time by up to 25%. This can reduce the overall scan time from 20 minutes to 9 minutes when combining GRAPPA with an ORF of 2 and the cut-corner technique. We also have shown that as stochastic noise increases with k-space subsampling, there is preservation of mean velocity, but the error of individual velocity vectors increases. In clinical situations where calculation of mean or peak velocities is important, such as evaluation of arterial stenoses, k-space subsampling is inappropriate. However, in situations where the integrity of the local velocity field is needed, such as 4D visualization techniques like streamlines or calculation of wall shear stress, a full acquisition may be more appropriate.