SNR-ADAPTIVE INHOMOGENEOUS NOISE CORRECTION COMBINED WITH UNIFORM FILTER AND SENSITIVITY MAP (INCUS) APPLYING TO DIFFUSION WEIGHTED IMAGE WITH PARALLEL IMAGING

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Introduction: Parallel imaging (PI) such as SENSitivity encoding (SENSE) [1] and standard surface-coil imaging techniques suffer from spatially inhomogeneous noise distribution introduced by inhomogeneous coil sensitivity and overwrapping noise, and a techniques of spatially nonuniform filtering were proposed [2]. An alternative technique named "Inhomogeneous Noise Correction combined with Uniform filter and Sensitivity map (INCUS)" proposed as a simpler and higher degree of freedom method, and demonstrated that application to two types of real-space filter, a linear and a structure adaptive, could improve inhomogeneous noise [3]. However it is difficult to optimally tune filtering strength depending on SNR or imaging sequence. The Wiener filter (WF) can adaptively control the SNR depending on target images but the standard WF, here we call uniform-WF, cannot be applied easily for correcting inhomogeneous noisy images since a general k-space filter is not spatially-dependently adjustable. A generally ideal WF for smoothing is given by $Hw=Ps/(Ps+Pn)$ where Ps and Pn respectively denote the power spectrum of ideal signal and noise; Pn is usually regarded as constant in whole applied domain such as k-space. But *ideal-Ps* of actually sampled noisy data cannot be known. We also proposed a *mean-Ps* method employing Pn of averaged multiple similar data instead of self-data (*same-Ps*) was practical and effective to improve SNR such as for diffusion tensor imaging (DTI) [4]. The purpose of this study was to propose and assess a modified INCUS (INCUS-WF) allowing to control variable absolute SNR as well as spatially-dependent SNR by combining WF-based INCUS technique and *mean-Ps* method.

Methods: Pn becomes spatially inhomogeneous $Pn(x)$ after sensitivity correction of PI data. Basic idea of INCUS-WF is that non-uniformly filtered image can be obtained by weighted summation of two WF-applied images by using the maximum and the minimum of $Pn(x)$ (Pn_{max} and Pn_{min}), and those can be obtained from a relative distribution of SNR map, $I_{snr}(x)$ and k-space data. In practical application of a standard Fourier WF, the Pn can be assumed to be constant in whole k-space if corresponding real-space $Pn(x)$ is slowly changed, and accordingly the average of $Pn(x)$, Pn_{mean}, can be measured by the average at the high-frequency portion of k-space. The ideal-WF (*FTWI*: *Hwi*) and the thresholding version of (*FTWT*: *Hwt*) respectively defined as: $Hwi=Ps/(Ps+\alpha Pn)$, and $Hwt=\max[0, Ps-\alpha Pn]/Ps$ [5] were used, α is a noise scaling factor to control smoothing strength. Whole process flow is shown in **Fig. 1**. Filtered images and the root-mean square error (RMSE) between filtered and the ideal (no noise) were compared between INCUS- and uniform-WF as a parameter of SNR (maximum of original image S_{orig} divided by mean noise-SD after sensitivity correction) and noise scaling α. The S_{orig} was produced by using measured SNR map and added simulated Gaussian noise to sufficiently higher SNR image. Here, single-shot EPI DWI brain images of healthy volunteer (6-axis, b=1000s/mm^2, matrix=192x192, slice thickness=3mm) acquired on 1.5T Toshiba Excelart/Vantage™ using 13-ch PI brain coil with SENSE-factor=x3. Isotropic-DWI image (geometric mean) of 6-different axis DWI images was used for *mean-Ps* method.

$S_{orig}(x)$: original inhomogeneous sensitivity image(given),
$I_{sense}(x)$: sensitivity map (given),
$g(x)$: g-factor (noise SD) map for SENSE imaging (given)
begin
1) Sensitivity correction : $S_{cor}(x)=S_{orig}(x)/I_{sense}(x)$
2) Obtain SNR map in real-space : $I_{snr}(x)= I_{sense}(x)/g(x)$
3) Obtain mean of noise-power $Pn(x)$ of $S_{cor}(x)$, Pn_{mean} by measuring at the high frequency portion in k-space.
4) Obtain noise-power map:
$Pn(x)= Pn_{mean}\{1/I_{snr}^2(x)\}/mean[1/I_{snr}^2(x)]$,
5) Normalize the SNR map
using $Isnr_{max}=max[I_{snr}(x)]$, $Isnr_{min}=min[I_{snr}(x)]$
$W_{snr}(x)=\{I_{snr}(x)-Isnr_{min}\}/\{Isnr_{max}-Isnr_{min}\}$
6) Apply two WFs(Hw_{max} and Hw_{min}) with Pn of $Pn_{max}=max[Pn(x)]$ and $Pn_{min}=min[Pn(x)]$:
$S_{cor.fil.max}(x)=Hw_{max}[S_{cor}(x)]$, $S_{cor.fil.min}(x)=Hw_{min}[S_{cor}(x)]$
7) Weighted summation of two filtered images to obtain nonuniformly filtered (INCUS) image
$S_{INCUS}(x)=W_{snr}(x)\cdot S_{cor.fil.min}(x)+\{1-W_{snr}(x)\}\cdot S_{cor.fil.max}(x)$
end

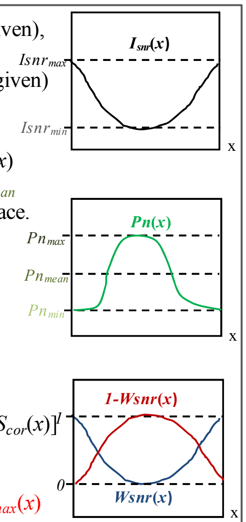

Fig.1 Process flow for INCUS-WF

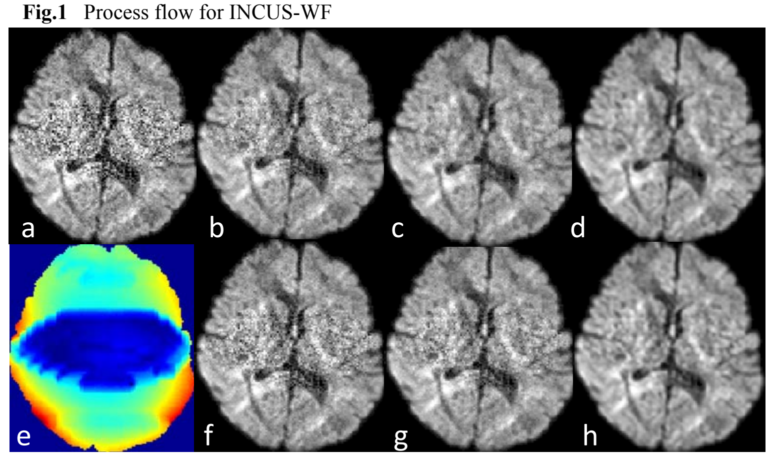

Fig. 2 Representative results for brain DWI. Original noisy images(SNR=17)(**a**), SNR-map of SENSE factor=x3(**e**), and filtered images of INCUS-WF (**b-d**) vs. uniform-WF(**f-h**), each with *FTWT_samePs* (**b,f**), *FTWI_meanPs*(**c,g**), and *FTWI_idealPs* (**d,h**). The center portions were better corrected by the INCUS-WF than by the uniform-WF and the *FTWI_meanPs* (**c**) provided the best quality in practically applicable filters.

Results and Discussion: Inhomogeneous noises on PI were naturally reduced by INCUS-WF while minimizing blur compared to uniform-WF, and the *ideal WF* with *mean-Ps* provided the nearest result to the ideal-WF in INCUS types (Fig. 2). Furthermore, smoothing strength of WF were adaptively controlled depending on the original data SNR, and the *mean-Ps* method introduced smaller errors close to the *ideal-Ps* method especially for lower SNR (Fig. 3a). The INCUS with *mean-Ps* provided the minimum errors at $\alpha=1$ that is theoretically optimum (Fig. 3b). Even if RMSEs were similar between INCUS-WF and uniform-WF, inhomogeneous noises were remained on the images with uniform-WF. In conclusion, INCUS-WF combining with *mean-Ps* method is a simple but very effective to adaptively and automatically improve both variable absolute SNR and spatially inhomogeneous SNR on DWI with PI.

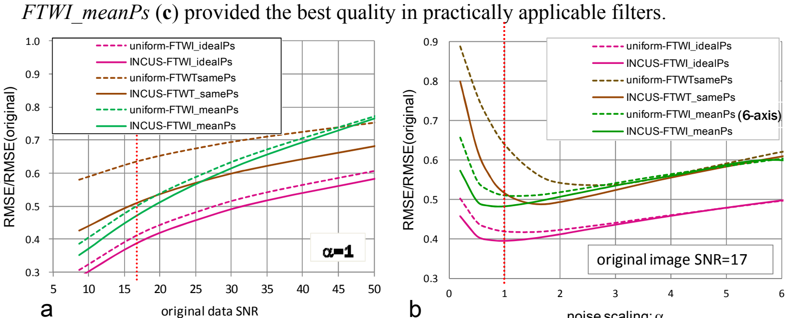

Fig. 3 RMSE ratios to the original noisy image as a function of original image SNR for α=1 (**a**) and noise scaling (α) for SNR=17 (**b**) each with INCUS-WF (solid line) and uniform-WF (dashed line) for three different types of FTW. INCUS-FTWI with mean-PS method (solid green) was the nearest to the ideal type in lower SNR.

References: [1] Pruessmann KP, *et al*. MRM 1999;42: 952-962. [2] Tsao J et al. ISMRM 2003, p780; [3]Kimura T *et al.*ISMRM 2006, p3212; [4] Kimura T *et al.*ISMRM 2006, p3209.