Bias field correction on 7T using novel 3D edge detector and high-order Legendre polynomial approximation.

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Target audience: researchers and clinicians interested in quantitative image analysis at ultra-high field

Purpose MR signal intensity at 7T is affected by strong non-uniformity artefacts, due to inhomogeneous RF fields, inhomogeneous reception sensitivity and patient's influence on the magnetic and electric field [1]. Correction of this effect is required for all MR image analyses, including segmentation, registration and functional modeling of dynamic data. *N3* algorithm by Sled is the de-facto standard for Bias field correction [2] but on ultra-high field MRI it shows its limits. We present the latest generation of our ***BiCal*** (Bias Calculation) algorithm for non-uniformity correction that depends only on two very general *assumptions*: **a)** bias field is multiplicative **b)** local signal intensity variation within a homogeneous tissue are caused by the bias field.

Methods

We detect inter-tissue borders with our proprietary edge detector sensitive to texture variations. Texture histogram difference is measured by Earth Mover Distance [4]. We avoided using the Gaussian blurring component characteristic to the standard Canny 3D edge detector. This resulted in superior geometrical precision of detected edges critical for this application. Voxels identified as edges and their adjacent voxels are marked. Also marked are background (air) voxels which are identified by signal < 2 times the level of estimated overall image noise. Unmarked voxels constitute a single binary mask **H** that represents all the regions of homogeneous tissue. Constrained Gaussian smoothing of **H** is performed such that for the given center voxel its vicinity across the detected edges is excluded from the smoothing aperture. The goal is to remove noise and partial volume effects before calculating discrete partial derivatives over the image. We next search for a slowly varying analytic scalar field **L(x,y,z) = log(Bias)** represented as the linear combination of ***3D Legendre polynomials*** up to degree **N**. The value of **N** is defined by the user and controls the spatial frequency of the resulting field. Useful results were achieved for **N** in the range [2-14] for our 7T brain data. Next the logarithm volume $\mathbf{P(x,y,z)=log(SI_{measured\_and\_smoothed})}$ is calculated. From *assumption* **a)** $\Rightarrow$ $\mathbf{P=log(SI_{true})+L}$ and **b)** $\Rightarrow$ $\boldsymbol{dP/dr=dL/dr}$ within **H**. We optimize polynomial coefficients of **L** over **H** so that the analytical partial derivatives {***d/dx, d/dy, d/dz***} provide the least squares fit of discrete partial derivatives of **P.** Cost function is a sum of square differences between partial derivatives for every voxel of **H**. Minimization problem results into highly over-determined linear system and is solved reliably using SVD. Finally, the resulting field **B(x,y,z) = exp(L)** is normalized so that its average value over non-air voxels is unity**.**

All acquisitions were performed on a 7T imager (Magnetom; Siemens, Erlangen, Germany) by using a volume-transmit 24-element receive coil array (Nova Medical, Boston, Mass). A 3D automatic shimming was first performed by adjusting all fist and second order shim currents, then shim performance was verified by using the interface on the imager console. This was followed by either sagittal (n=2) or axial (n=2) 3D MPRAGE sequences acquired on four volunteers (28-54 year old, 3 males). The acquisition parameters were: TR/TE/TI=2.6/2600/1100 msec, FA=6°, 248 SL=0.6 mm, 346 × 323 x 248 matrix, acceleration factor of two. To measure accuracy four volumes were evaluated. 100 closely adjacent pairs of seeds of WM and GM were placed on 10 equidistant slices of each volume. SWM_i, SGM_i denote the signal intensity of $\mathbf{i_{th}}$ white and gray matter seed. Non-uniformity ***U*** was expressed as StdDev()/Avg() averaged over all seeds. To avoid trivial solutions, we set the parameters of BiCal and N3 to preserve, within 2%, local tissue contrast $\boldsymbol{C=SWM_i/SGM_i}$. Software was implemented using MSVC++ 2012 compiler, Intel TBB. Tests were performed on Intel i7-3970 processor under Windows 7.

Results: *BiCal* with 12-th degree Legendre polynomial approximation of ***L*** (a total of 455 coefficients) was compared to *N3* algorithm with optimized parameters (noise=0.01, fwhm=0.2 and aggressive setting for the field smoothness=10mm to keep comparison conservative). For all cases, all samples, and both algorithms, **C** was distributed 1.38 ± 0.11 (mean ± standard deviation). Before non-uniformity correction, ***U*** was 27.5% for the WM, 29.9% for the GM. ***U*** was significantly better (WM=12.6%, GM=12.5%) for *BiCal* than for N3 (WM=19.4%, GM=21.9%). Figure 2 shows a representative result. Note better visualization of the cerebellum by *BiCal* compared with *N3* in this midsagittal view. *BiCal* run took a total of 15 seconds, including 6 sec for edge detection and 9 sec for the optimization. BiCal is fully parallel so all 12 threads of the processor were 100% busy.

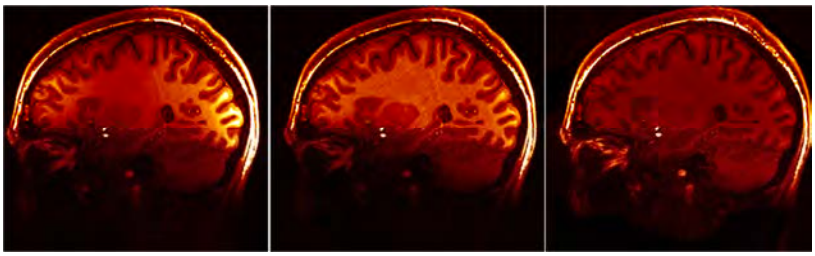

figure 2. Representative result: Original , N3-corrected , and BiCal-corrected volume

	WM U%	GM U%
a (T1w)	28.5/14.5/6.5	33.5/19.8/12.9
b (T1w)	28.8/15.7/10.1	27.8/17.6/10.7
c (T2w)	26/23.3/18.4	28.5/23.8/12.1
d (T2w)	26.7/24/15.5	29.9/26.4/14
average	27.5/19.4/12.6	29.9/21.9/12.5

figure 3. **U%** for patients {a,b,c,d}x{WM,GM} as Original/N3/BiCal

Discussion: While some components of the BiCal were proposed in the literature [3], suboptimal methods were used to exclude high-gradient voxels. Legendre polynomials of degree >3 were dismissed as computationally expensive. We found that good results are achievable with the polynomials of up to 14^{th} degree. After several revisions BiCal algorithm has numerous possibilities for improvement. Windows GUI application is freely available.

Conclusions: For ultra-high field brain images, a 35% average decrease (from *U* = 19.4% to 12.6%) in WM non-uniformity and a 43% average decrease (from *U=21.9% to 12.5%)* in GM non-uniformity was achieved using the latest version of *BiCal* algorithm compared to N3. This improvement was significant, as it was not associated with degradation of contrast between the gray and white matter.

References:

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