Objective
Finding brain, skull and scalp surfaces has important applications, especially in EEG/MEG modelling, where this allows one to use more accurate models than those often used at present. BET2 (Brain Extraction Tool v2) is a fast and fully automated tool for extracting brain, inner and outer skull and scalp surfaces from MR images. It ideally requires a pair of T1- and T2-weighted images, preferably of <2mm resolution. BET2 can output mesh surfaces (useful for BEM-based algorithms) and filled images (useful for FEM-based methods).

BET2 is based on BET [Smith 2002], which finds the brain boundary given an MR image. BET can attempt to find external skull surface voxels, but does not fit a surface to this, and the resulting crude “skull” image contains a relatively large number of false negatives and positives.

Method
BET2 uses high-resolution T1- and T2-weighted images, though can run (with less accuracy) given only a T1. First, the brain surface is found using the original BET algorithm using the T1. The T2 is then registered to the T1, normally using FLIRT [Jenkinson 2002]. Generally, in an MR image, the skull appears darker than brain and other tissues. Its intensity is comparable to that of background. In T1-weighted images, CSF is dark, sometimes as low as air/skull. In T2, CSF is bright, and muscles are often dark (making muscle hard to distinguish from skull).

The relative intensity of brain and scalp on T1 can vary a lot from one scanner to another. In order to increase the robustness to these variations, we constrain the maximum scalp intensity relative to the brain intensities. To avoid the problem of over-bright scalp, we compute a maximum intensity threshold; we take the “robust range” of intensities within the extracted brain volume (this being the 2% and 98% points in the cumulative histogram of brain voxel intensities) and increase the upper value by 10% of this range. We then clamp all voxels (in the whole-head image) to this.

For each vertex on the brain surface, the perpendicular direction is searched outwards for estimation of 3 points - the inner and outer skull, and the outer scalp. Various rules are used, which are now presented in simplified form.

First, the outer scalp point is found, by combining the outermost non-dark T1 point and the outermost non-dark T2 point (thresholds determined from robust histogramming).

Next, the inner skull point is found as a combination of searches (outwards from the brain) for the “first dark” T1 and T2 points. The outer skull point is harder to find robustly, due to topological complications in certain regions and the presence of bone marrow within the skull; a more complex combination of the T2 and T1 profiles is used to identify the most likely point, followed by correction on the basis of proximity to the inner skull point. This approach detects correctly the outer skull points in much of the head, but fails in the lower areas, where tissues and skull topology are too complex. Thus we have an alternative algorithm for those areas. To determine the area in which this alternative algorithm is needed, we use a priori spatial knowledge: this area has been manually determined in standard space and consists of a lower, frontal region.

We use FLIRT to derive a standard space transform matrix and transform this mask into the space of our data. The outer skin and inner skull points are detected as explained above. The outer skull is detected as the first point over a 35% threshold after the first point under a 25% threshold on the T1 profile. If this first point is too far (greater than 7mm) outside the inner skull we revert to the simplified assumption that the outer skull point is 0.5mm outside the inner skull point. Finally, an image is created for each of the 3 surfaces, using the points found; these are slightly blurred (HWHM=3mm) primarily to increase the “attraction area” for mesh fitting. Deformable meshes are then fit to these images for all surfaces, with cross- and self-intersection prevented.

Example Results
Fig. 1 (bottom of poster) shows BET2 surfaces overlaid onto an example T1-weighted image. Red volume: original BET brain volume. Blue: inner skull surface. Green: outer skull surface. Yellow: scalp surface.

Fig. 2 shows skull surfaces overlaid onto a co-registered CT image for validation.

Conclusions
We are hopeful that BET2 may prove useful as a fully automated method of deriving brain/skull/scalp surfaces for use in such applications as EEG/MEG modelling. BET2 has been made freely available as part of FSL. For fuller detail, see a technical report at www.fmrib.ox.ac.uk/analysis/research/bet

References

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