Bibliography on Image Registration

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Abstract

Reference for image registration are collected. The focus is on image registration for the human brain, particularly for functional neuroimaging. This includes geometrically unwarping of EPIs, intrasubject motion correction, intersubject atlas registration, etc. Pointers to image registration programs are given as well as a list of brain templates.

This structured bibliography is part of a larger collection of bibliographies see http://www.imm.dtu.dk/~fn/bib/Nielsen2001Bib/. The bibliography is written in LaTeX and BIBTeX and should be available both as HTML and PostScript.

The bibliography is probably far from complete, but new references are added whenever the author finds new material and has the time to add them. You can email the author if corrections are required or you have found references that you fell ought to be included: fn@imm.dtu.dk.

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1 Keywords

co-registration, image co-registration, image matching, image realignment, image registration, inter-subject registration, linear registration, matching, motion correction, multi-modal image matching, multimodality matching, realignment, registration, registration techniques, resampling, reslicing, rigid matching, robust registration, spatial resampling, spatial interpolation, warping.

2 General references

(Toga, 1998) is an edited volume about brain warping. (Bro-Nielsen, 1996) is a Ph. D. thesis which summarizes some of the methods in operation in 1996. Another is (Maintz and Viergever, 1998).

A general image registration survey is found in (Brown, 1992).

3 Methods

Table 1 display the different types of image transformations or "motion models". These can both be performed in 2D and 3D. *Linear transformation* is only global scaling and rotation, — no translation (when presented in the stadard formulation). With the use of *homogeneous coordinates* translation can be made with a matrix multiplication, thus rigid, similarity and affine transformation can be made with a matrix multiplication. *Shear transformation* can make a parallelogram from a rectangle. Nonlinear warps can have a "symmetric prior" (Ashburner et al., 2000; Ashburner et al., 1999). The transformation can be confined to a specific dimension, e.g., inplane realignment.

Table 2 shows the cost functions associated with image registration. There are several variation of the cost functions:

- Rebinning in mutual information, e.g., 64 (Freire and Mangin, 2001a), or the use of fuzzy membership, smoothing of joint histogram, also called the "grey level cooccurrence matrix" (GLCM).
- Apodization with weighting of the cost function near the edges of the image to avoid local minima (Jenkinson et al., 2002).
- Multigrid optimization where the image registration parameters are first determined on a low-resolution image with large voxel size. The parameters on this first level is used as initial values of the parameters on the next finer level, see, e.g., (Maes et al., 1999)
- Excluding (mask) or weighting voxels differently, e.g., to spatial normalize patients with local lesions (Brett et al., 2001). This functionality is available in the spatial normalization procedure of the SPM2 and FSL package in spm_normalise and flirt, respectively, see Table 7.

Category	Subcategory	Subsubcategory	Description	Reference
Rigid			Only rotation and translation	
Non-rigid	Similarity		Rigid body and global scaling	
—	Affine		Rotation, translation and scaling	
—	Nonlinear	Polynomial basis	E.g., AIR	(Ingvar et al., 1994)
—	—	Cosine basis	E.g., SPM	
—	—	Thin-plate splines		(Bookstein, 1989; Evans et al., 1991; Evans et al., 1994)
—	—	Elastic		(Miller et al., 1993), e.g., FMG
—	—	Fluid		(D'Agostino et al., 2004)
—	—	Nagel-Engelmann		(Nagel and Enkelmann, 1986; Hermosillo et al., 2001)
—	—	Piecewise affine	E.g., Talairach	
—	—	Infinitesimal affine		(Nielsen et al., 2002)

Table 1: Image transformations. Motion models. Restrictions on the motion.

Table 3 shows resampling and interpolation methods. Further references for this step are (Thévenaz et al., 2000; Meijering et al., 2001).

VTK implements affine, "grid" and thin-plate spline transformations with nearest neighboor, trilinear or tricubic interpolation on meshes, regular sampled, structure and unstructured grids http://www.kitware.com, (Gobbi and Peters, 2003).

In Matlab 3D spatial resampling is implemented in the "interp3.m" function with nearest neighbor, linear, cubic and spline interpolation methods.

Type	Subtype	Description	Reference
Point			(Arun et al., 1987)
Point	External fiducial markers		
	Internal landmarks	E.g., "head of caudate" and other matched with Procustes algorithm (least squares)	(Evans et al., 1994), Evans, 1991
—	Robust	Robust alignment with Rayleigh-Bessel function	(Schormann and Dabringhaus, 2001)
Line			
Plane		"Surface Matching Technique"???	(Pellizzari et al., 1989)
Volume			(Collins et al., 1994)
—	Square distance	'Least square' or L^2 mismatch	
—	Normalized correlation		
—	Correlation coefficient		
—			
—	Ratio image uniformity	'Wood's criteria'	(Woods et al., 1992)
—	Correlation ratio	An asymmetric measure: $\eta(\mathbf{y}\vert\mathbf{x}) = \frac{\mathsf{V}[\mathsf{E}[\mathbf{y}\vert\mathbf{x}]]}{\mathsf{V}[\mathbf{y}]}$	(Roche et al., 1998b; Roche et al., 1998a)
—	Joint entropy		
—	Mutual information	Also refered to as relative entropy	(Collignon et al., 1995; Viola and Wells III, 1995; Wells III et al., 1996; Maes et al., 1997; Studholme et al., 1997)
—	Normalized mutual information		(Studholme et al., 1998)
—	Entropy correlation coefficient		(Maes et al., 1997)
—	With segmentation and *a priori* volumes		(Ashburner et al., 1997)
—	Mutual information to probabilistic tissue class labels		(D'Agostino et al., 2004)

Table 2: Cost functions: Discrepancy and similarity measures. See also (Jenkinson et al., 2002, table 1).

Name	Description	Reference
Nearest neighbor		
Trilinear	Also called ‘linear’	
Cubic		
Spline		
Windowed sinc	Also called ‘truncated sinc’	e.g., (Hill et al., 1994)
Mixed linear/windowed sinc		
Unwindowed sinc		
Chirp-z	Fourier domain analogue of sinc interpolation	(Woods et al., 1999; Rabiner et al., 1969)
Mixed linear/chirp-z		

Table 3: Spatial resampling. Partially from http://bishopw.loni.ucla.edu/AIR3/overview.html

4 Geometric unwarping of EPI

Unwarping of EPI can be approached as an multi-modality non-rigid image registration problem: EPI scans can have geometric and intensity distortions and are to be match with anatomical scans, e.g., a MRI T1 image (Studholme et al., 1999; Studholme et al., 2000). In (Kybic et al., 2000) the deformation field is modeled with splines. (Andersson and Skare, 2002) describes an unwarping algorithm for diffusion weighted EPI.

Other references for unwarping are (Jezzard and Balaban, 1995; Munger et al., 2000). An overview appears in (Hutton et al., 2002)

Name	Method and description	Reference
Field-map undistortion (*)	Undistortion by a field (phase) map	(Cusack and Papadakis, 2002; Cusack et al., 2003), http://www.mrc-cbu.cam.ac.uk-/Imaging/fieldmap_undistort/
FUGUE *	'FMRIB's Utility for Geometrically Unwarping EPIs' Program for EPI unwarping included in FSL	(Jenkinson, 2001), http://www.fmrib.ox.ac.uk/fsl/fugue/
PRELUDE *	Utility program for FUGUE	http://www.fmrib.ox.ac.uk/fsl/fugue/
Unwarp *	Correction of movement-by-susceptibility induced variance	(Andersson, 2001), http://www.fil.ion.ucl.ac.uk/spm-/toolbox/unwarp.html, toolbox for SPM99. Integrated in SPM2.

Table 4: Correction for geometric distortion.

5 Motion correction

In motion correction the brain (and head) is typically regarded as a rigid body where only rotation and translation in space are possible. Introductions to this subject are (Cox, 1996; Brammer, 2001). This type of registration can also be found under names such as PET-PET registration, MRI-MRI registration or MR/MR registration.

Some of the problems associated with motion correction are

- Interpolation errors when reslicing.
- 'Movements at certain frequencies can interact with the physics and temporal dynamics of the image acquisition protocol' (Woods et al., 1999).
- In functional neuroimaging head movements can be correlated with the paradigm (Hajnal et al., 1994; Bullmore et al., 1999). This is also called *task-related motion* or *stimulus correlated motion*. Even submillimeter movement can have an influence (Field et al., 2000; Desmond and Atlas, 2000).
- Applying a non-robust motion correction on data with large activations can produce spurious activations (Freire and Mangin, 2001a; Freire and Mangin, 2001b). This problem becomes more serious with larger MR scanner field strengths (e.g., 3T compared with 1T) as well as larger activation with addition of contrast agents such as MION. Contour-based methods should be less sensitive to the confound (Biswal and Hyde, 1997). A robust algorithm is also describe by (Hsu et al., 2001).
- Differencies in the field of view among the images cause the cost function to have many local mimima (Jenkinson et al., 2002).
- Within scan motion can produce complex confounds that separate slice-timing and realignment procedures cannot fully correct and 4D algorithms are required (Bannister et al., 2002).

A visualization method for the motion artifacts are described in (Lacey et al., 1999; Thacker et al., 1999), see also http://www.tina-vision.net/tina4/tina_tk_fmrimotion.html.

Tools for motion correction of 3D functional neuroimages are presented in table 5. Other motion correction methods are described in (Minoshima et al., 1992; Snyder, 1996; Hill et al., 1994).

Motion correction for list-mode PET is possible with optical tracking systems, e.g., with the POLARIS system (Watabe et al., 2004). A real-time system with real-time image-based motion detection during fMRI scan and subsequent adjustment of slice position is described in (Thesen et al., 2000).

(Ardekani et al., 2001) compared 4 algorithms. Given the range of noise and misalignments imposed the results tended to show the following order (with the most accurate first): SPM99, AFNI98, TRU, AIR.

The motion parameters (and derived parameters) can be included as nuisance parameters in modeling, e.g., in columns of a design matrix of a general linear model (Friston et al., 1996; Lund et al., 2005; Brett, 2005; Johnstone et al., 2005). This can have large impact on the summary image obtained by statistical tests (Lund et al., 2005). (Grootoonk et al., 2000) find that interpolation errors account for the residuals and suggest using sinusoids as the transformation between the movement and the design variables. An application for EEG-fMRI data with patients with epilepsy is described in (Lemieux et al., 2007). This approach included "scan nulling".

In MRI motion correction is usually performed for fMRI, but it might have some utility for structural (anatomical) MRI (sMRI/aMRI) scans as well (Kochunov et al., 2006).

Table 5: Motion realignment tools. A star '*' indicates that the tool is readily available on the Internet.

Name	Description	Reference
AFNI *	Squared distance cost function implemented by the `imreg` and `2dImReg` programs for 2D registration and `3dvolreg` for 3D registration	(Cox, 1996), http://afni.nimh.nih.gov/afni-/AFNI_Help/imreg.html
AIR *		AIR 3 (Woods et al., 1998a), AIR 5: http://bishopw.loni.ucla.edu/AIR5/
DART	An algorithm that operates in the Fourier domain (k-space)	(Maas et al., 1997)
Flirt *	Motion correction using Flirt (McFlirt) Multiresolution optimization with apodization	(Jenkinson et al., 2002; Jenkinson and Smith, 2001; Jenkinson and Smith, 2000; Bannister and Jenkinson, 2001) http://www.fmrib.ox.ac.uk/fsl/flirt/
INRIAlign *	Robust cost function	(Freire et al., 2002; Freire and Mangin, 2001a), http://www-sop.inria.fr/epidaure-/software/INRIAlign/index.html
Reg *	Rigid-body or affine intramodal registration software by Philippe Thévenaz	(Thévenaz and Unser, 1998; Thévenaz et al., 1995; Unser et al., 1993) http://bigwww.epfl.ch/thevenaz/registration/
RS	"Registration software" written as an AVS module with brain surface segmentation and PET-PET and PET-MRI registration	(Alpert et al., 1996)
SPM *	Implemented in the `spm_realign.m` function	(Friston et al., 1995)
TRU *	(Seems to be the same as Thévenez' "reg")	

6 Coregistration

Coregistration or *multimodality image registration* is more complicated than motion alignment since the gray-levels of the tissue types in the different image modality, say PET and MRI, may not correspond to each other.

Early voxel-intensity based algorithms are described in (Woods et al., 1993; Ardekani et al., 1995; Andersson et al., 1995). Table 6 displays coregistration tools. Note that most image registration software that include some form of the mutual information will be able to do co-registration.

Table 6: Coregistration tools. A star '*' denotes that the tool is easy available.

Name	Transform	Description	Reference
AIR *		`alignlinear` in AIR3.0	(Woods et al., 1993) http://www.loni.ucla.edu/NCRR/-Software/AIR.html
AMIR			(Ardekani et al., 1995)
CBA		Commercial program from *Applied Medical Imaging*	http://www.appmed.se
Flirt *			(Jenkinson et al., 2002; Jenkinson and Smith, 2001; Jenkinson and Smith, 2000) http://www.fmrib.ox.ac.uk-/fsl/flirt/
IIO	Rigid	"Interative Image overlay". Manual alignment.	(Willendrup et al., 2004)
IPS	Rotation/-translation	"Interactive Point Selection". Semi-automated landmark-based with least-squares optimization, applied for neuroreceptor studies. Part of the MARS (Multiple Algorithms for Registration of Scans) package.	(Willendrup et al., 2002a; Willendrup et al., 2002b; Willendrup et al., 2004), http://www.nru.dk/people-/willend/mars/
MATCH	Non-linear		(Hermosillo et al., 2002; Chef d'Hotel et al., 2002; Hermosillo et al., 2001). Used for co-registration in, e.g., (Fize et al., 2003)
MIPAV *	Linear, thin plate spline	Landmark-based least-squares fitteing	(Arun et al., 1987), http://mipav.cit.nih.gov/
MIRIT		Commercial coregistration program based on mutual information	(Maes et al., 1997), http://bilbo.esat.kuleuven.ac.be-/web-pages/downloads/Mirit-/Mirit.html
MPI (?)		Interactive tool	(Pietrzyk et al., 1994)
MRIWarp *	Non-linear	General registration with mutual information and correlation coefficient (and least squares) cost function	(Kjems et al., 1999a; Kjems, 1998; Kjems et al., 1999b) http://hendrix.imm.dtu.dk-/software/mriwarp/
RS		"Registration software" written as an AVS module with brain surface segmentation and PET-PET and PET-MRI registration	(Alpert et al., 1996)

Name	Transform	Description	Reference
RView8	Rigid	(mmvreg/rview)	http://noodle.med.yale.edu/˜cs-/software/software.html
SPM *		Both mutual information registration and registration based on WM/GM/CSF segmented images are implemented (in SPM99). SPM2 incorporates a number of different cost functions related to mutual information (The "Coregister" button and the `spm_coreg.m` function)	(Ashburner and Friston, 1997; Ashburner et al., 1997; Collignon et al., 1995; Wells III et al., 1996; Maes et al., 1997; Studholme et al., 1998), http://www.fil.ion.ucl.ac.uk/spm/

IPS, IIO, AIR 5.0 and SPM99 are compared on MRI to FDG-PET and altanserin-PET coregistration in (Willendrup et al., 2004). SPM99 and AIR are found to perform between on simulated FDG-PET-to-MRI co-registration than the manual methods of IPS and IIO. With the altanserin radiotracer, where there it finds little or no 5HT2A binding in cerebellum, the manual methods perform better.

Another comparison of co-registration algorithms appears in (Pfluger et al., 2000).

7 Spatial normalization

Discussion of the origins of spatial normalization appears in (Fox, 1995). Early reference to spatial normalization are (Fox et al., 1985; Friston et al., 1989). Other names are *inter-subject brain image registration*, *intersubject registration*, *atlas warping*, ...

In functional neuroimaging spatial normalization insures that the functional results can be compared to the anatomy in multiple subject studies. In (Poldrack and Devlin, 2007) the issues of reporting the functional activation with respect to the anatomy is discussed.

Table 7 lists tools for spatial normalization, while further spatial normalization methods are described in (Bajcsy et al., 1983; Bajcsy and Kovacic, 1989; Gee et al., 1993; Kosugi et al., 1993; Minoshima et al., 1994; Davatzikos, 1996; Christensen et al., 1997; Kochunov et al., 2000; Thévenaz and Unser, 2000). (Andersson and Thurfjell, 1997) report a system for intra and intersubject PET registration (perhaps it is used in the CBA program?). (Thompson et al., 1997) describe a fluid deformation for cortical surfaces. A method for "inter-mouse" warping is described in (Falangola et al., 2005).

7.1 Comparison and evaluations

Talairach normalization has been found to result in a "sulcal variation zone" of 1.5–2.0 centimeters measured against landmarks (Steinmetz et al., 1990). For the medial temporal lobe standard deviation on landmarks have been found to be one or three millimeter, depending on optimal or suboptimal parameters in non-linear basis-based spatial normalization (Salmond et al., 2002), see also (Ramsøy, 2007, appendix 3). The problems associated with spatial normalization of the hippocampus have been discussed in (Krishnan et al., 2006). AFNI, SPM99 and ART have been compared in (Ardekani et al., 2004).

The effect of different spatial normalization (affine AIR, MRIWarp) is evaluated on functional O-15 positron emission tomograhy (PET) data in (Kjems et al., 1999a) with canonical variate analysis, and the study finds that the non-linear MRIWarp procedure is superior to the affine.

An elastic warping is compared to and affine transformation and an SPM96 registration in (Gee et al., 1997), and it finds peak activation from an analysis of functional images higher for the warping than for the affine procedure.

In (Davatzikos et al., 2001b) MR-MR SPM96, PET-PET SPM95, MR-MR SPM99 and STAR are compared and it is found the STAR results in the lowest P-values.

The influence of the template has been investigated with the four choices using SPM99 for spatial normalization of PET FDG images (Gisbert et al., 2003): One choice with the default H20 template provided by SPM and two choices with a constructed FDG templates. One FDG template was constructed from the subjects by averaging spatial normalized FDG PET images that was normalized to the default SPM template, and another FDG template that was constructed by averaging FDG images whose deformation was estimated from MRI images. The last choice did not construct an FDG template and instead warped the subject PET-scans based on deformations estimated from the MRI images. A reported maximum z-score ranged from 4.13 to 4.60.

Table 7: Spatial normalization algorithms and software. A star ("*") indicates that a public program is available.

Name	Description	Reference
AIR3 *		(Woods et al., 1998b; Woods et al., 1999) http://bishopw.loni.ucla.edu/AIR3/
ANIMAL	Also called MNI_ANIMAL. Non-linear registration. First step is similar to AutoReg. Second step uses a deformation field	(Collins et al., 1995), http://www.bic.mni.mcgill.ca-/users/louis/MNI_ANIMAL_home/readme-/readme.html
ART	Many-parameters algorithm	(Ardekani, 2003; Ardekani et al., 2004)

Name	Description	Reference
AutoReg	Also called MNI_AutoReg. Linear transformation with a cross-correlation cost function	(Collins et al., 1994), http://www.bic.mni.mcgill.ca-/users/louis/MNI_AUTOREG_home/readme/
CBA	Translation, scaling, rotation and second transformation	(Greitz et al., 1991; Ingvar et al., 1994)
CHSN *	"Convex Hull Spatial Normalization"	(Lancaster et al., 1999; Downs et al., 1994) http://ric.uthscsa.edu-/projects/chsn/chsn.html
DARTEL *	Diffeomorphic image registration	(Ashburner, 2007), ftp://ftp.fil.ion.ucl.ac.uk-/spm/spm5_updates
FMG	Elastic	(Schormann and Zilles, 1998; Schormann et al., 1996), Email Thorsten Schormann.
HAMMER *	Elastic	(Shen and Davatzikos, 2002; Shen and Davatzikos, 2003; Davatzikos et al., 2001a), https://www.rad.upenn.edu/sbia/software-/index.html#hammer
HBA (*)	"Human Brain Atlas". Linear and nonlinear image registration and template	(Roland et al., 1994) http://www.dhbr.neuro.ki.se/Hba/
LIPSIA (*)	Linear and nonlinear normalization in the LIPSIA package	(Lohmann et al., 2001; Thirion, 1998)
MRIWarp *	Non-linear warp	(Kjems et al., 1999a; Kjems, 1998; Kjems et al., 1999b) http://hendrix.imm.dtu.dk-/software/mriwarp/
SN	9-parameter affine transformation	(Lancaster et al., 1995) http://ric.uthscsa.edu-/projects/spatialnormalization.html
SPM *	Default is a $7 \times 8 \times 7$ basis function in SPM99. SPM2 includes functionality to weight/mask voxels.	(Friston et al., 1995; Ashburner and Friston, 1996; Ashburner and Friston, 1999), http://www.fil.ion.ucl.ac.uk/spm/
STAR	Elastic warping	(Davatzikos, 1997)

7.2 Brain templates

A large part of the spatial normalization algorithms require a target to match to: a *template* — aka. "anatomical textbook", cf. (Miller et al., 1993)). A number of the templates for the human brain is listed in table 8. Further templates/brain atlases are pointed to in (Toga and Thompson, 2000). There is a discrepancy between the Talairach and the MNI templates, and a piecewise affine transformation between the two has been suggested (Brett, 2002). This does not fully compensate (Chau and McIntosh, 2005; Lancaster et al., 2007; Lancaster et al., 2006).

According to John Ashburner an O-15 H2O template can be used to normalize FDG PET image without "disastrous" results SPM mailing list 2002-01-21.

Table 8: Templates: Some of the standard human brains used in stereotaxic alignment.

Name	Age	Modality	Description	Reference
colin27	Adult	T1	MNI single subject (Colin Holmes). Also used in BrainWeb and the default template in SPM96. (Approximately?) in the same space as MNI305 Also distributed with MRIcro as ch2.	(Holmes et al., 1998), SPM99 spm_templates.man. http://www.mrc-cbu.cam.ac.uk/Imaging/-Common/downloads/Colin/.
MNI	Adult	T1, T2, PD, EPI, PET, SPECT	Name for the MNI* templates	
MNI152	Adult	T1, T2, PD	Standard templates in SPM99, distributed volume are smooth with 8mm FWHM in 2mm resolution	SPM99 spm_templates.man
MNI305	Adult	T1	ICBM standard, also distributed in SPM99	SPM99 spm_templates.man, (Collins et al., 1994; Evans et al., 1993; Collins, 1994), ftp://ftp.bic.mni.mcgill.ca-/pub /avgbrain/
'Woods 1999'	Adult	T1, T2 EPI	Based on ten subjects in Talairach scaled space	(Woods et al., 1999)
Visible Human	Adult		Brain from the Visible Human Project	http://www.nlm.nih.gov/-research/visible/-visible_human.html
VAPET	Adult		Used at the VA Medical Center, Minneapolis	
CBA		Cryosections	'Computerized brain atlas', Dept. Neuroradiology, Karolinska Institute. Included in the CBA program Also called "Greitz space".	(Greitz et al., 1991; Seitz et al., 1990; Thurfjell et al., 1995)
HBA			'Human Brain Atlas' from Karolinska Institutet	(Roland et al., 1994)
ECHBA			New HBA. Re-acquired HBA used in European Computerised Human Brain Database	(Schormann et al., 1999; Roland et al., 1999)
'BIT'			Warped single subject	(Lancaster et al., 2001)
EVA833	Elderly		Based on 833 elderly subjects	(Quinton et al., 1999)
—		Ligand PET	[carbonyl-11C]WAY-100635, [11C]raclopride	(Meyer et al., 1999)
—	Adults(?)	PET L-DOPA	Based on 12 subjects	Andreas Meyer-Lindenberg, SPM mailing list 2001-11-20

Name	Age	Modality	Description	Reference
CCHMC	Children	T1	Template based on 148 children age 5–18.	http://www.irc.chmcc.org-/chips.htm, Marko Wilke, http://www.irc.chmcc.org, SPM mailing list 2001-12-17
PAN	—	External measurements	Preauricular-nasion Used in EEG. Not a template. Coordinates defined on individual basis.	
SUIT	Adult		Cerebellum	(Diedrichsen, 2006), http://www.bangor.ac.uk-/˜pss412/imaging/suit.htm
Talairach	(Elderly)	Drawings	Original Talairach images. No MRI exists.	(Talairach and Tournoux, 1988)
Schmahmann	Adult	Drawings, JPG, (T1)	Book with images of cerebellum from colin27	(Holmes et al., 1998; Schmahmann et al., 2000; Schmahmann et al., 1999; Schmahmann et al., 1996; Makris et al., 1996)

7.2.1 Animal brain templates

(Horsley and Clarke, 1908) describe a stereotaxic space for the macaque defined from measurements on Macaca mulatta (Macacus rhesus) and a few cases of Macaca fascicularis (Macacus cynomolgus).

Name	Species	Modality	Description	Reference
B2K	Baboon	T1 MPRAGE, O15-Water PET		(Black et al., 2001b), http://www.nil.wustl.edu-/labs/kevin/ni/b2k/
N2K	Macaca Nemestrina (pig-tailed macaque)	T1, PET		(Black et al., 2001a), http://www.nil.wustl.edu-/labs/kevin/ni/n2k/p1.htm
'Pig space'	Pig (Göttingen minipig^{TM})	MRI		(Andersen et al., 2001), SPM Mailing list, 2001-8-2
Ratlas	Rat	MRI		(Schweinhardt et al., 2003), http://mr.imaging-ks.nu/expmr.htm
(Rat)	Rat			(Schwarz et al., 2006)
Template Atlas	Macaca fascicularis	Drawings	Bicommisural coordinate system with zero at anterior commissure	http://www.elsevier.com-/homepage/sah/pbm/

Table 9: Animal templates. See http://www.kopfinstruments.com/Atlas/ for a list of animal brain atlases.

(Erwin et al., 1999) describes a functional atlas for the monkey lateral geniculate nucleus with respect to directions in visual space. This is available as "Atlas of a Rhesus Lateral Geniculate Nucleus (LGN)" from http://soma.npa.uiuc.edu/labs/malpeli/atlas/.

7.2.2 Conversion

From ‘Template Atlas’ (TA) to (Szabo and Cowan, 1984) (SC)

$$\mathrm{AP_{SC}} = \mathrm{AP_{TA}} + 17\mathrm{mm}, \quad (1)$$
$$\mathrm{DV_{SC}} = \mathrm{DV_{TA}} + 4\mathrm{mm}, \quad (2)$$

and from ‘Template atlas’ to (Shantha et al., 1968) (SMB)

$$\mathrm{AP_{SMB}} = \mathrm{AP_{TA}} + 17\mathrm{mm}, \quad (3)$$
$$\mathrm{DV_{SMB}} = \mathrm{DV_{TA}} + 8\mathrm{mm}. \quad (4)$$

These transformations were taken from http://www.elsevier.com/homepage/sah/pbm/atlas/Tempindex.html.

8 Validation and comparison

Type	Description	Reference
Spatial normalization	HBA, SPM(96) and “linear” compared on PET	(Sugiura et al., 1997), (Sugiura et al., 1999)?
MRI/PET coregistration	AIR and SPM(96) compared	(Kiebel et al., 1997b; Kiebel et al., 1997a)
CT, MR, PET coregistration	Internet-based blinded evaluation of 8 algorithms	(West et al., 1997), http://www.vuse.vanderbilt.edu-/~image/registration/
Spatial normalization	Comparison of an affine (AIR), a polynomial (AIR), an cosine (SPM) and a elastic deformation (FMG)	(Crivello et al., 2002)
Spatial normalization		(Hellier et al., 2001; Hellier et al., 2002; Hellier et al., 2003)

Table 10: Validation

A list of validation studies are available in table 10. A comparison of early image registration algorithms appears in (Strother et al., 1994).

In “The Retrospective Registration Evaluation Project” (West et al., 1997; Fitzpatrick et al., 1998) a number of algorithms for CT-MR and PET-MR image registration has been evaluated and the results are available on the Internet from http://www.vuse.vanderbilt.edu/~image/registration/

9 Application

9.1 Image-guided neurosurgery

Uses of spatial normalization in image-guided neurosurgery (IGNS): (Nowinski et al., 2000; Nowinski et al., 1998). (St-Jean et al., 1998) use a deformable version of the Schaltenbrand and Wahren atlas for the basal ganglia and thalamus. Database construction: (Finnis et al., 2000).

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the default SPM template, and another FDG template that was constructed by averaging FDG images whose deformation was estimated from MRI images. The last choice did not construct an FDG template and instead warped the subject PET-scans based on deformations estimated from the MRI images. A reported maximum z-score ranged from 4.13 to 4.60.

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