Automatic Registration Tool (ART) Program V1.0
Users' Guide

Toshiba Medical Systems

January 13, 1999

Contents

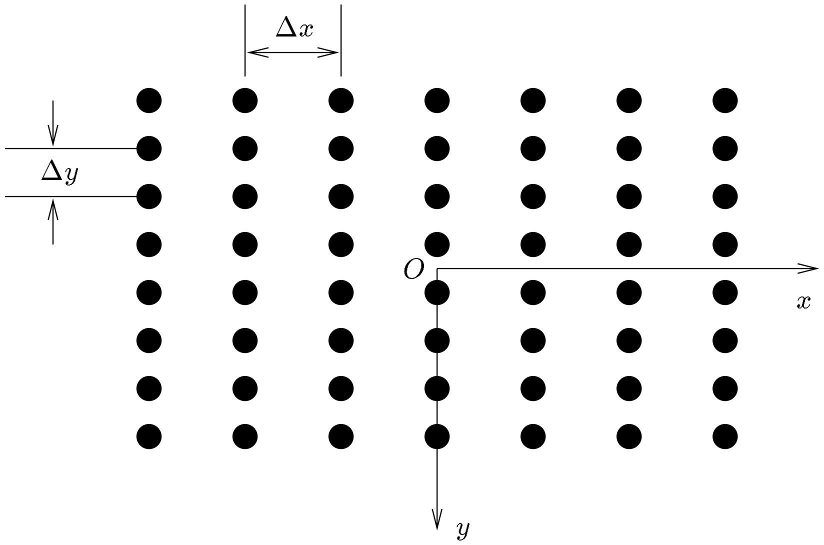


Figure 1: Schematic representation of an $N \times M$ image slice ($N = 7$, $M = 8$) and the image coordinates system.

1 Introduction

The *Automatic Registration Tool* (ART) is a brain image registration software package, designed for use by medical imaging researchers. With ART, it is possible to register three-dimensional (3-D) anatomical brain images such as CAT[1] and MRI[2] to functional brain images such as SPECT[3] and PET[4]. This document describes the theory and practice of image registration using ART.

In the remainder of this section, we will describe some of the conventions and terminology that are used in this document for describing 3-D images.

1.1 Matrix size

A 3-D image is assumed to consist of a number of 2-D slices. If there are K slices where each slice has a width of N picture elements (pixels) and a height of M pixels (Fig. 1), then the 3-D image is said to have a *matrix size* of $N \times M \times K$ pixels.

1.2 Image coordinates system

According to ART's convention, the x-axis points from image left to right and the y-axis points from top to bottom. The x and y axes are shown in Fig. 1. The direction of the z-axis is determined by the right-hand rule. In Fig. 1, the z-axis points into the page. The origin of the coordinates system is taken to be the exact center of the image volume.

1.3 Voxel size

Each pixel is assumed to represent a small volume element (voxel) of size $\Delta x \times \Delta y \times \Delta z$ mm^3 which is centered around that pixel. Thus, as shown in Fig. 1, Δx is the distance

[1] Computed axial tomography.
[2] Magnetic resonance imaging.
[3] Single photon emission computed tomography.
[4] Positron emission tomography.

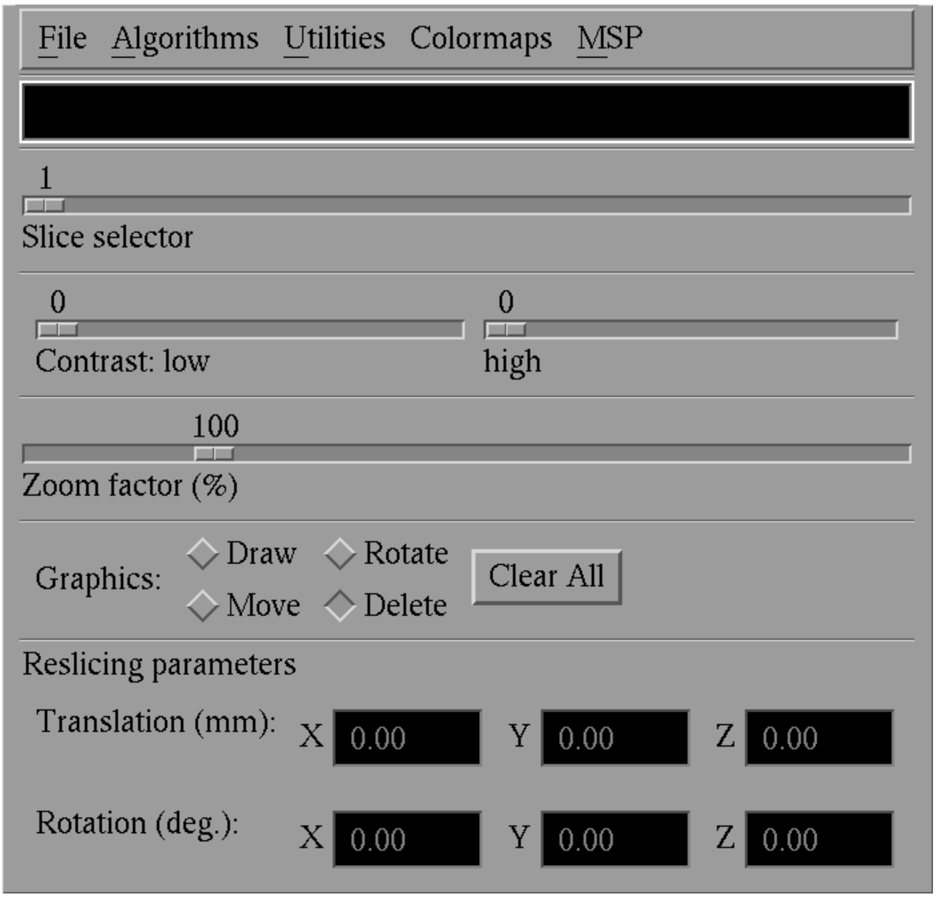


Figure 2: ART's main window.

(in mm) between two adjacent pixels in the x-direction; and Δy is the distance between two adjacent pixels in the y-direction. Similarly, Δz represents the distance between two neighboring pixels in the z-direction. Alternatively, Δz may be thought of the distance between two adjacent image slices.

Given the voxel dimensions, the real world coordinates (in units of mm) of each pixel with respect to the origin may be obtained precisely. For example, in an $N \times M \times K$ image, the coordinates of the pixel in the upper left corner of the first image slice is given by $[-\Delta x(N-1)/2, -\Delta y(M-1)/2, -\Delta z(M-1)/2]$.

2 Starting ART

To start ART, type: *art*. The *main* window (Fig. 2) will appear. In order to ensure proper functioning of ART, users must add two setup commands in their shell setup file. These commands are explained below.

2.1 The ARTHOME environment variable

When ART starts up, it examines the ARTHOME environment variable in order to determine the available colormaps. The ARTHOME environment variable is normally set to /usr/local/art. If the ARTHOME environment is not already defined for you,

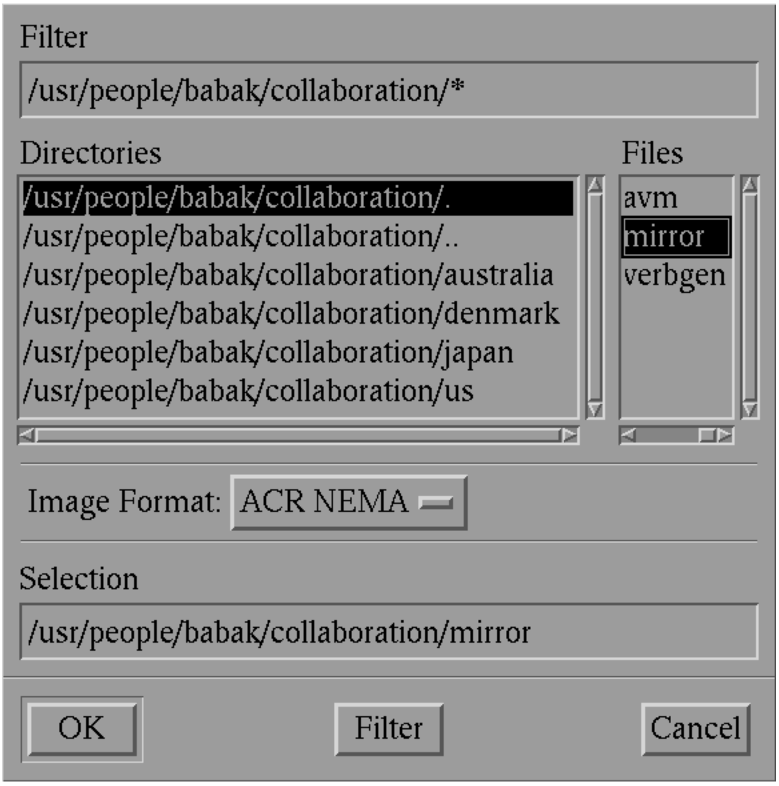


Figure 3: The image file selector (FS) window.

it must be set in your shell setup file. For example, if you are using the C Shell, the following command must be added to your *.cshrc* setup file:

setenv ARTHOME /usr/local/art

2.2 The stacksize

Some of the algorithms in ART use recursion, that is, a function repeatedly calls itself. Recursion is supported by a memory structure called the stack. ART requires a large stacksize for proper functioning. For this reason, it is recommended that the users maximize the available stacksize in their systems. This can be achieved by adding the following command to the *.cshrc* setup file:

unlimit stacksize

3 File Selector Windows

Operations such as loading or saving images or registration parameters require the user to select a file. For example, to load an image, you must first select the file in the hard disk in which the image is stored. For such operations, ART will prompt the user by displaying a *file selector* (FS) window. An example FS window is shown in Fig. 3. This section describes the operation of FS windows in detail.

3.1 Changing directories

The current directory is shown at the top of the FS window in the **Filter** text area. In Fig. 3, the current directory is:

/usr/people/babak/collaboration

Under the current directory, there may be several subdirectories and files. The subdirectories are shown in the **Directories** list. The files are shown in the **Files** list. For example, in Fig. 3, there are four subdirectories (australia, denmark, japan, us) and three files (avm, mirror, verbgen) under the current directory. Two extra entries (“.” and “..”) are always shown in the **Directories** list. The entry “..” represents the parent of the current directory (in this case /usr/people/babak) and “.” represents the current directory itself.

There are three ways for changing the current directory:

(a) Double click on one of the entries in the **Directories** list.

(b) Select one of the entries in the **Directories** list by a single mouse click and click the **Filter** button.

(c) Type in the full path of the directory (plus a “/*” at the end) in the **Filter** text area at the top, followed by a carriage return.

3.2 File selection

As in the case of changing directories, the are three methods for selecting a file in an FS window:

(a) Double click on the file in the **Files** list.

(b) Select the file in the **Files** list by a single mouse click and click the **OK** button.

(c) Type in the full path of the file in the **Selection** text area (just above the **OK** button), followed by a carriage return.

4 Loading Images

In order to load an image, select **Open ...** from the **File** menu (Fig. 4). This will bring up the FS window shown in Fig. 3 in which you must select the image file and format. Detailed instructions for selecting the image file from an FS window are given in section 3.

Note that after the FS window appears, the program will freeze and you cannot perform any other operation until you select an image file (see below) or cancel the image loading operation by clicking the **Cancel** button.

4.1 Image format selection

ART currently supports three types of formats:

- ACR NEMA type formats (e.g., Dr. View)
- ANALYZE
- RAW

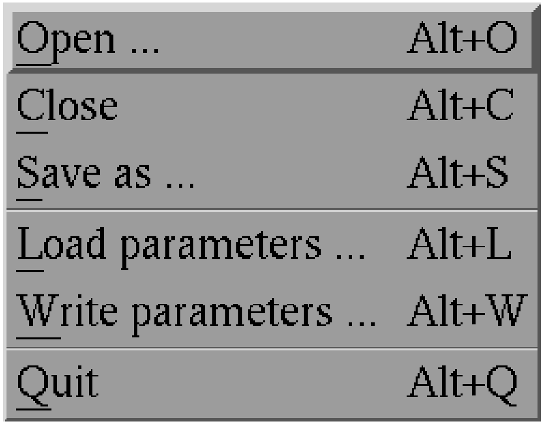


Figure 4: The **File** menu.

These formats can be selected from the **Image Format** option menu on the FS window (Fig. 3). The default format is ARC NEMA. If either of the ACR NEMA or ANALYZE formats are selected and there are no errors (e.g., you may not have read permission for the selected image file), the image will be loaded and displayed on the screen. However, if the RAW format is selected, some more information are requested from the user (see below).

4.2 Reading raw image format

If the user selects the RAW image format from the FS window, ART will request some additional information from the user by displaying the *read raw image* window shown if Fig. 5. As in the case of the FS window, all operations freeze until the user clicks the **Read** button to load the image or the **Cancel** button to cancel the operation.

In order to load an image in RAW format, four pieces of information are required: the image matrix size (section 1.1); image voxel size in mm (section 1.3); size of the image file header in bytes; and the image data type (char or short). The header size tells ART from where to start reading the image data. For example, if the header size is specified to be h, then ART will skip the first h bytes from the beginning of the file and starts reading the image data from the $h + 1$st byte.

After you specify the above parameters, click the **Read** button to load and display the image.

5 Image Viewing

Once you have successfully loaded an image, it will be displayed on the computer screen. Several images may be loaded and displayed simultaneously. However, at any given time, only one of the images is the *selected* image. A red border drawn around the image indicates the currently selected image. Figure 6 displays a PET (Fig. 6a) and an MRI (Fig. 6b) image. The red border around the PET image identifies it as the currently selected image. Most of the image operations that you perform in ART apply to the selected image. For example, "zooming" will only magnify the selected image.

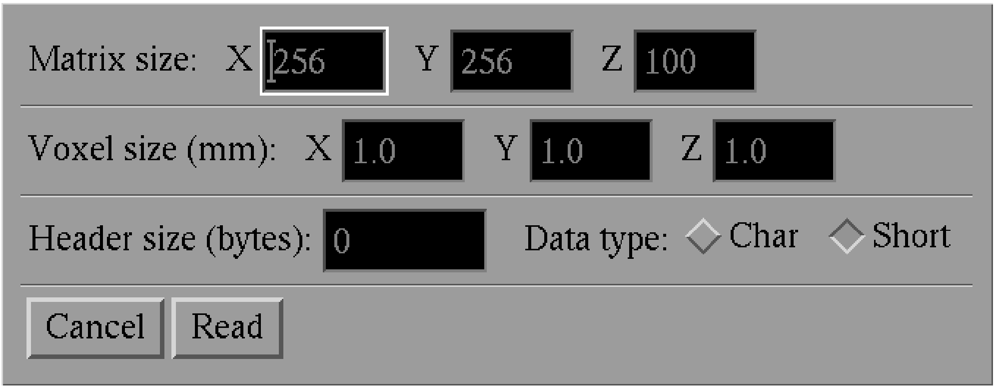
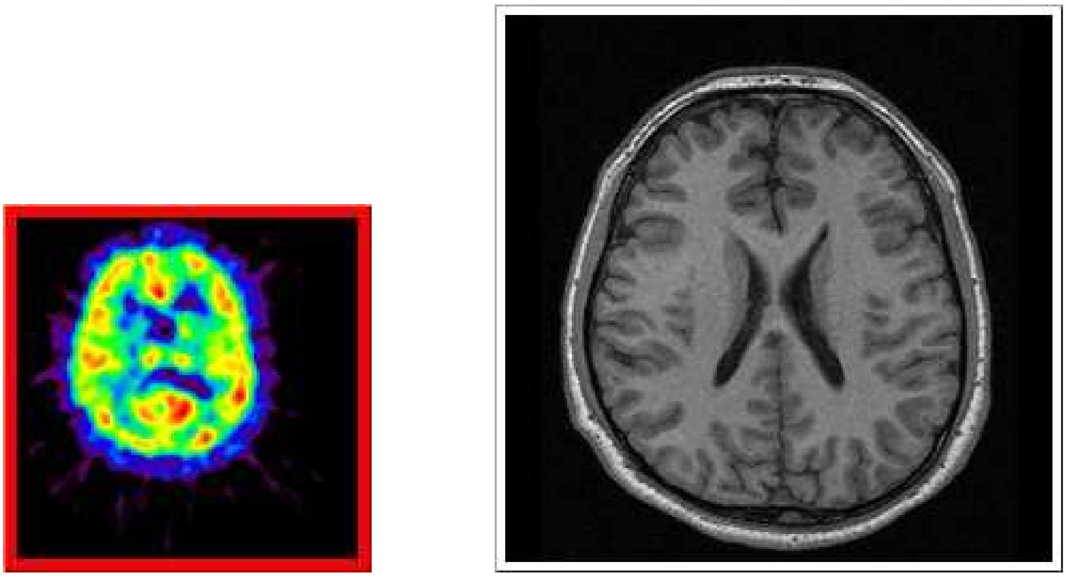


Figure 5: The *read raw image* window.



(a) (b)

Figure 6: (a) Selected image. (b) Displayed but not selected image.

After an image is loaded, several changes occur in the appearance of the main window (Fig. 7). The text area at the top (below the menu bar) will show the image filename. The values of the **low** and **high** contrast sliders change to the 0.05% and 99.95% percentiles of the image gray level histogram, respectively. Let L and H denote the values of the **low** and **high** contrast sliders, respectively. For example In Fig. 7, $L = -881$ and $H = 5308$. This means that approximately 0.05% of the total number of pixels in the image have values less than L (greater than H). When displaying an image, ART sets any pixel value below L equal to L and any pixel value greater than H equal to H. Changing the values of the **low** and **high** contrast sliders will change the contrast of the selected image.

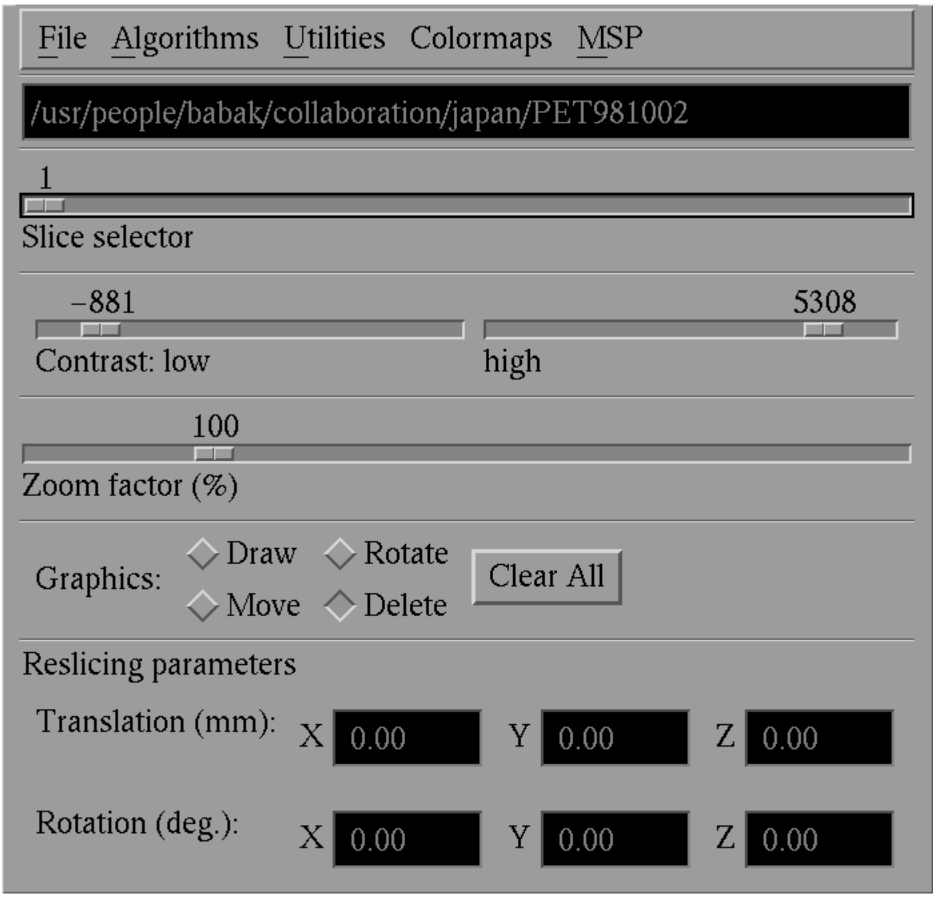


Figure 7: ART's main window after an image has been loaded.

5.1 Image selection

Most of the functions of ART are performed on the selected image. Therefore, before performing an operation on an image, the user must first select the image. There are three ways that an image may become the selected image:

(1) Whenever a new image is loaded/created, it automatically becomes the selected image.

(2) The user can select an image by a single mouse click on the image window.

(3) If a selected image is closed, ART will automatically select another image (the image with the lowest image number).

When you select a new image, the following changes occur in ART's main window:

(1) The selected image filename will be displayed in the text area at the top (below the menu bar).

(2) Value of the **Slice selector** changes to the slice number displayed on the selected image window.

(3) Values of the **low** and **high** contrast sliders change to the contrast levels of the selected image.

(4) Value of the **Zoom factor** slider changes to the zoom factor of selected image.

5.2 Viewing different image slices

In order to view a different slice of an image, select the image first. Different slices may then be viewed by changing the **Slice selector** slider in ART's main window (Fig. 7).

5.3 Changing the image contrast

The contrast of the selected image may be changed by changing the **low** and **high** contrast sliders. Let L and H denote the values of the **low** and **high** contrast sliders, respectively. For example In Fig. 7, $L = -881$ and $H = 5308$. When displaying an image, ART sets any pixel value below L equal to L and any pixel value greater than H equal to H. The pixels values in the interval from L to H are then scaled so as to maximize the gray level dynamic range.

5.4 Image magnification/demagnification

The selected image may be magnified or demagnified using the **Zoom factor** slider in the main window.

5.5 Changing the colormap

The colormap of the selected image may be changed by selecting a different colormap from the **Colormaps** menu (Fig. 8a).

ART has a number of predefined colormaps in the ARTHOME directory. These are the files with *.colm* extensions. When ART starts up, it examines the ARTHOME directory in order to find the available colormaps. It then lists the names of these files as options in the **Colormaps** menu in ART's main window. For example, *umber* is an option in the **Colormaps** menu shown in Fig. 8a. This implies that a file named *umber.colm* exists in the ARTHOME directory.

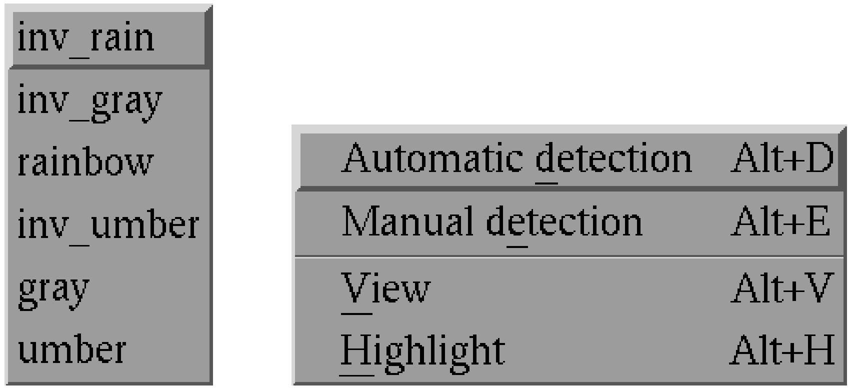
Users can create their own colormaps and add them to the list of colormaps available to ART. For example, you may create a file called "mycolormap.colm" and copy it in the ARTHOME directory. Then, the next time you run ART, "mycolormap" will be available in the **Colormaps** menu in ART's main window. The format of the *.colm files is very straightforward. Each file contains 256 lines representing 256 different colors. Each line consists of 3 numbers between 0.0 and 1.0 representing the relative RGB values for that color.

5.6 Closing images

The selected image may be closed using **Close** from the **File** menu (Fig. 4). Closing will free all the memory and other resources used for displaying the image. When an image is closed, ART will automatically select another image (the image with the lowest image number).

6 Detecting and Viewing the Mid-Sagittal Plane

This section describes the operations of detecting and viewing the mid-sagittal plane (MSP). ART uses the MSP's for manual or semi-automatic image registration.



(a) (b)

Figure 8: (a) The **Colormaps** menu. (b) The **MSP** menu.

6.1 Automatic MSP detection

To start the automatic MSP detection process, select the image whose MSP you are intending to detect and click **Automatic detection** from the **MSP** menu (Fig. 8b). A window similar to the one shown in (Fig. 9a) will appear informing you that the automatic MSP detection process is in progress. You may cancel the process by clicking the **Cancel** button in this window. After the MSP is detected, two changes occur in the ART graphical user interface (GUI):

(1) The window shown in Fig. 9a will automatically disappear.

(2) If the image on which you started the MSP detection process is still the selected image, the location of MSP plane will be highlighted on the image as shown in Fig. 9b.

ART only allows one MSP detection process to run at any given time. Therefore, if you try automatic MSP detection on another image while the MSP detection process is running, ART will issue a warning message and refuse to initiate the process.

The algorithm used for automatic MSP detection locates the plane with respect to which the image exhibits the maximum left-right symmetry in 3-D. Details of this algorithm are given in the paper by B. A. Ardekani *et al.* "Automatic Detection of the Mid-Sagittal Plane in 3-D Brain Images," *IEEE Transactions on Medical Imaging*, Vol. 16, No. 6, pp. 947–952, 1997.

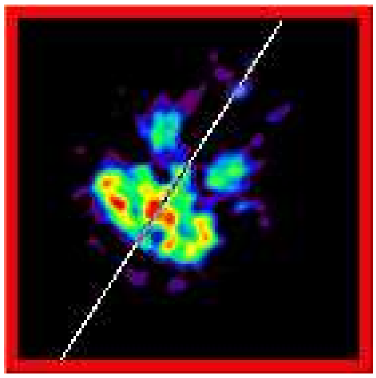
6.2 Highlighting the MSP

The MSP highlight on a selected image may be turned on/off using **Highlight** from the **MSP** menu (Fig. 8b). If you highlight the MSP on an image without detecting it first, ART will highlight the default location of the MSP which is the zx-plane. Try this and see what happens.

6.3 Viewing the MSP

When the MSP is detected, either automatically or manually (see below for the manual detection method), it can be viewed by selecting **View** from the **MSP** menu (Fig. 8b). The MSP image will be displayed in a 512×512 window as shown in Fig. 10.

(a)



(b)

Figure 9: (a) This window indicates that an automatic MSP detection process is in progress. The process may be cancelled by clicking the **Cancel** button. (b) The location of the detected **MSP** may be highlighted on the image.

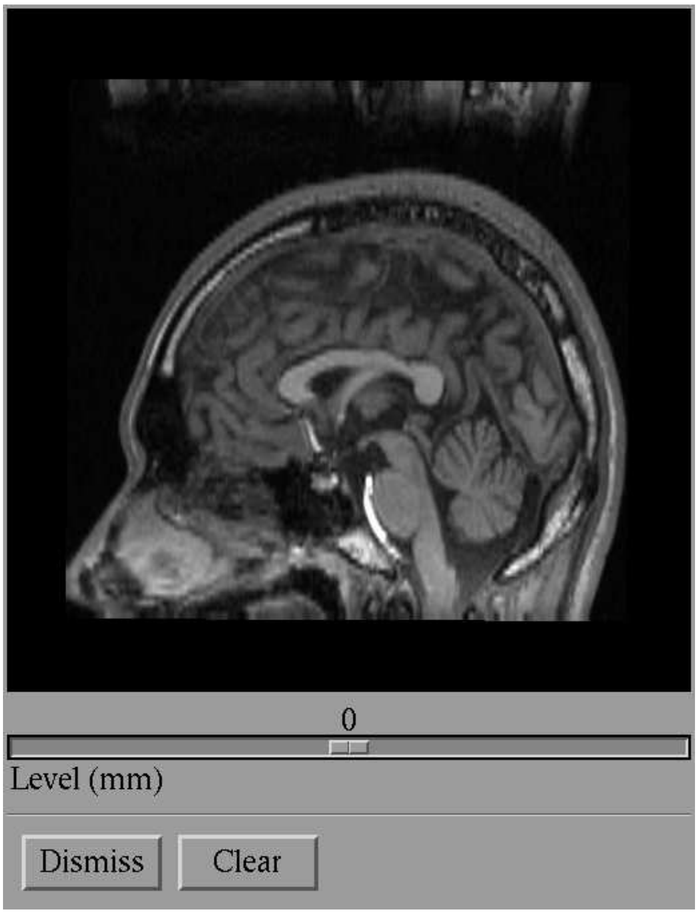


Figure 10: The MSP image.

In addition to the MSP image, there are three other GUI elements in the MSP image window shown in Fig. 10. The **Dismiss** button will dismiss the displayed MSP image. We will discuss the function of the **Clear** button in subscetion 10.2. The slider labeled **"Level (mm)"** is used for viewing different planes parallel to the MSP. If you move the slider to the right, the image of a sagittal slice parallel to the MSP and located in its positive side (towards positive x-direction) will be shown. If you move the slider to the left, the sagittal slice shown will be parallel to the MSP but located in its negative side. The number shown by the slider is the perpendicular distance in millimeters between the displayed sagittal slice and the MSP plane.

6.4 Manual MSP detection

If for some reason the automatic MSP detection routine fails to detect the MSP accurately (e.g., brain asymmetry due to disease), then we may obtain the MSP manually. For this purpose, it is necessary to outline the MSP on several image slices using the simple graphics capabilities provided by ART. To do this, select the image for which you intend to find the MSP. Select **Draw** on ART's main window (Fig. 2). You can then draw straight lines on the image window. Draw lines on several slices as shown in Fig. 11. If you make a mistake, you can move, rotate or delete drawn lines as follows.

To move a line, select **Move** and position the mouse pointer near the center of the line. The pointer changes to a "hand" symbol. You may then move the drawn line by moving the mouse while holding down any mouse button.

In order to rotate a line, select **Rotate** and position the mouse pointer near either ends of the line. The pointer changes to a "rotation" symbol. You may then rotate the line by moving the mouse while holding down any mouse button. The center of rotation will be the other end of the line.

To delete a line, select **Delete** and position the mouse pointer near the center of the line. The pointer changes to a "pirate" symbol. You may then delete the line by clicking any mouse button.

The **Clear All** button on ART's main window will delete all the lines that you have drawn on the selected image on all slices. So be careful not to click this button inadvertently.

After you have drawn several lines indicating your guess for the approximate location of the MSP on several slices as in Fig. 11, select **Manual detection** from the **MSP** menu (Fig. 8b). ART will fit the best plane (in a least squared error sense) through the lines and automatically highlights the location of the detected MSP. If you decide that the location of the detected MSP is inaccurate, you may adjust the lines that you have drawn or add more lines on different slices (perhaps on slices further apart). Then click **Manual detection** from the **MSP** menu again to obtain a new estimate of the MSP. After finding a visually accurate MSP, you may click **Clear All** in the main window to delete all the lines that you have drawn.

7 Registration Parameters

ART is designed for intrasubject 3-D brain image registration. This type of registration can usually be achieved by making one image the "target" image and the other image the "object" image. The object image is then rotated and translated in order to match the target image. This is like manipulating a rigid body in space. There are six degrees of freedom. Three translations in x, y and z directions and three rotations

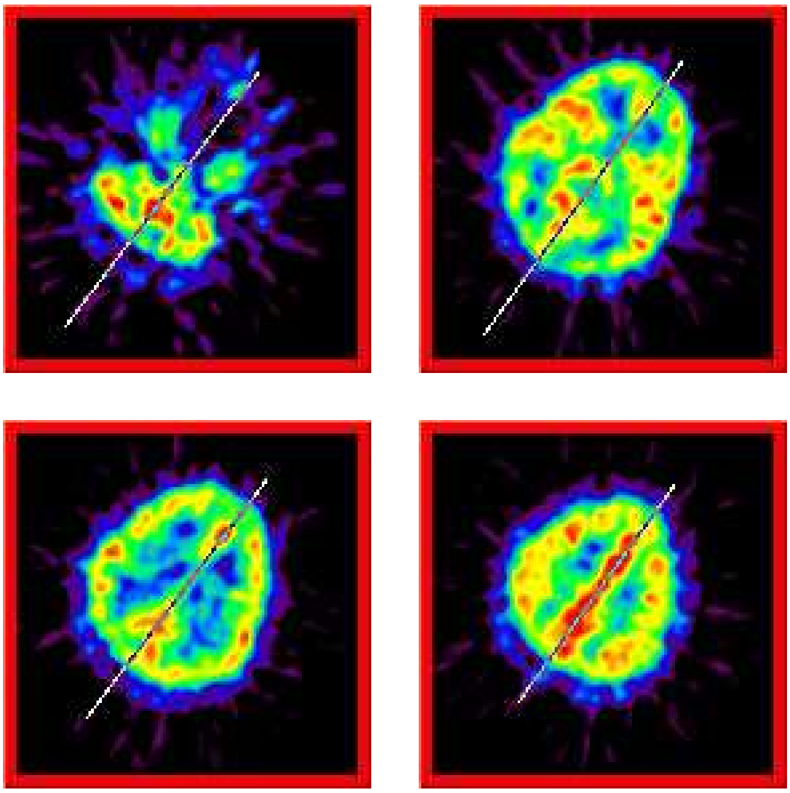


Figure 11: The approximate location of the MSP is manually marked on four different slice in an image volume.

about the x, y and z axes. The key to a correct registration is knowing how much to translate in each of the three directions and how much to rotate about each of the three axes[5]. The six parameters that specify a given transformation are denoted here as the *registration parameters.* ART always shows the *current* set of registration parameters in the main window (Fig. 2). When ART is first started, they are all zero. The current registration parameters (the ones shown in ART's main window) can change in several different ways. The first and most basic way is to manually enter their new values in ART's main window.

7.1 Zeroing the registration parameters

Clicking **Zero parameters** from the **Utilities** menu (Fig. 12) will set all of the six registration parameters equal to zero. Try entering some numbers manually and then select **Zero parameters** from the **Utilities** menu.

7.2 Reversing the registration parameters

Usually the registration parameters are meant to register an object image, say image O, to a target image, say image T. This means that when image O is resliced using these parameters, the result will be matched to the target image T. If on the other hand we decide to make image O the target image and reslice image T in order to

[5]The order of the transformations is also important.

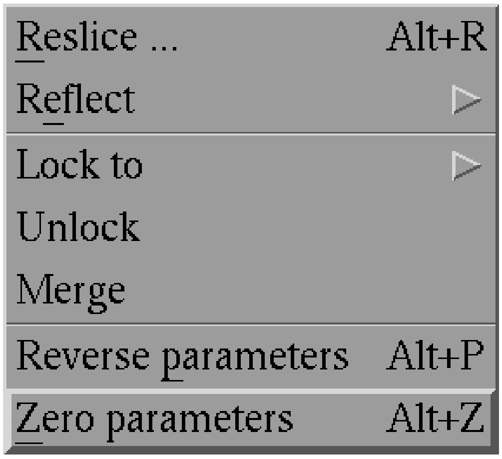


Figure 12: The **Utilities** menu.

match it to image O, we must use the reverse of these parameters. That is, the parameters have to be reversed. There is no trivial way of doing this. For example, negating the parameters usually does not achieve this. In ART, this can be done by selecting **Reverese parameters** from the **Utilities** menu (Fig. 12). Try entering some numbers manually and then select **Reverse parameters** from the **Utilities** menu. You will see that the registration parameters will change.

7.3 Saving the registration parameters

The current set of six registration parameters may be saved to a file in the hard disk. In order to save the parameters, select **Write parameters** from the **File** menu (Fig. 4). The will bring up a FS window. In this window, select the file in which you want to save the current registration parameters.

Saving the registration parameters is useful because when you perform a registration between two images, you can save the registration parameters that you obtain and use them later in order to register the two images. That way you do not have to do the registration process again.

7.4 Loading registration parameters

A set of registration parameters that have been saved in the hard disk can be reloaded into ART by selecting **Read parameters** from the **File**. When you read a new set of registration parameters, the current set of parameters will be replaced by the new parameters. The old set will be lost.

8 Image Reslicing

Assume that you have an image with a matrix size of $N \times M \times K$ pixels and a voxel size of $\Delta x \times \Delta y \times \Delta z$ mm^3. Suppose you would like to *reslice* the image to have the new matrix size $N' \times M' \times K'$ and the new voxel size $\Delta x' \times \Delta y' \times \Delta z'$ mm^3. Furthermore, the target image may have a different orientation from the original (object) image. The present section describes the procedure for performing this type of image reslicing using ART.

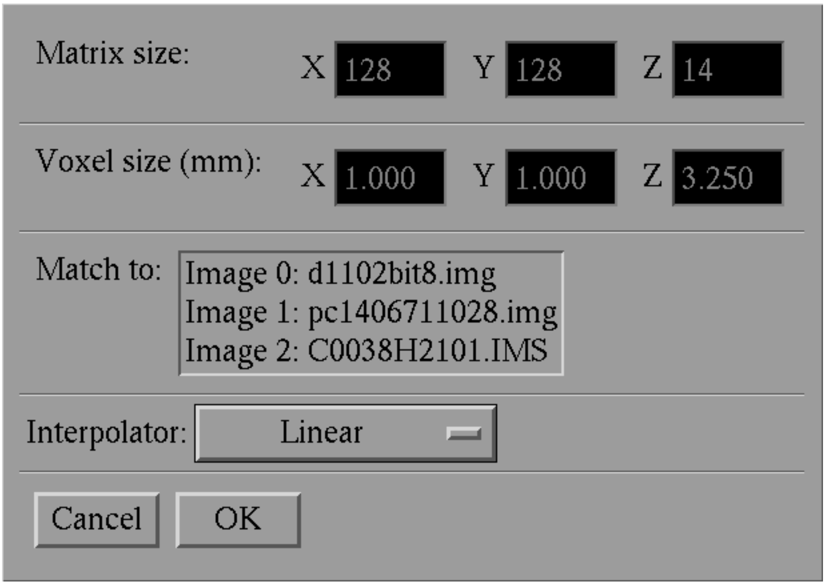


Figure 13: ART *reslicing dialog* (RD) window.

8.1 Selecting the object image for reslicing

In order to start image reslicing, select the object image that is to be resliced and click **Reslice ...** from the **Utilities** menu (Fig. 12). ART will bring up the *reslicing dialog* (RD) window shown in Fig. 13. Note that while this window is being displayed, you cannot perform any other operations from ART's main window. However, you may still change the object image by clicking on another image.

8.2 Selecting the size of the target image

The matrix size and the voxel size of the target image are shown at the top of the RD window. For example, in Fig. 13 they are $128 \times 128 \times 14$ and $1.0 \times 1.0 \times 3.25$ mm^3, respectively. By default, when the RD window is first displayed, the matrix size and the voxel size are those of the currently selected image. However, the user may and usually does change these values before reslicing. There are two possible methods for changing these parameters:

(1) Enter them manually in the RD window.

(2) Click on one of the file names shown in the **"Match to"** list. This list contains the file names of all the images that are currently loaded and are being displayed by ART. Clicking on one of these file names will change the matrix and voxel size parameters to those of that image.

8.3 Interpolation method

Image reslicing requires interpolation. ART supports three different types of interpolations:

(1) Linear.

(2) Nearest neighbor.

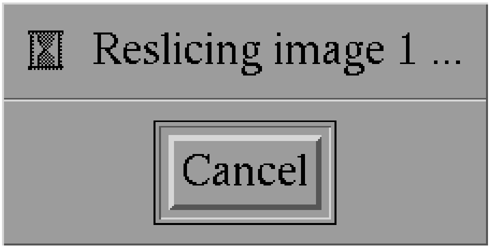


Figure 14: This window indicates that a reslicing process is in progress.

(3) Sinc.

The particular type of interpolation used for the current reslicing operation may be selected from the **Interpolation** option menu (Fig. 13). The default method is linear interpolation.

8.4 Starting the reslicing process

After you have selected the object image to be resliced, the desired matrix and voxel sizes of the target image, and the interpolation method, the reslicing process may be started by clicking the **OK** button of the RD window (Fig. 13). After this, the window shown in Fig. 14 will appear informing you that a reslicing process is in progress. You may cancel the reslicing operation by clicking the **Cancel** button in this window.

8.5 Image transformation

During the reslicing process, the object image undergoes the transformations given by the current registration parameters shown in ART's main window. The exact transformation depends on the definition of the coordinates system, center of rotation and the order of transformations. ART's coordinates system convention has already been covered in section 1.2. The center of rotation in ART is always the origin of the coordinates system. It remains to specify the order of transformations. During reslicing, ART transforms the object image in the following order:

(1) Rotation about the z-axis.

(2) Rotation about the x-axis.

(3) Rotation about the y-axis.

(4) Translations in x, y and z directions.

8.6 Saving the resliced image

After the reslicing is completed, the window shown in Fig. 14 will automatically disappear and the resulting resliced (target image) will be displayed. At this point, you may want to save this image to the hard disk. This may be done by clicking **Save as ...** in the **File** menu (Fig. 4). An FS window will appear which allows you to choose the file name and format of the saved image. In general, any other image may be selected and saved in a similar manner.

9 Image Fusion

Suppose that you register image 0 to image 1 and then reslice image 0 to match image 1 using the resulting registration parameters. Lets denote the resliced image as image 2. After reslicing, you may want to compare images 1 and 2 side-by-side or superimposed (merged) in order to assess the quality of the registration. ART allows any two images that have the same matrix size to be superimposed (merged) or *locked* together for side-by-side display. This is the topic of the present section.

9.1 Locking images for side-by-side display

ART allows two images that have the same matrix size to be *locked* together. Locking two images will have the following effects:

(1) If you change the currently displayed slice on one image, the displayed slice on the second image will automatically change to the same slice number.

(2) If you magnify/demagnify one of the two locked images, the other one will also be magnified/demagnified by the same factor.

(3) If you place the mouse pointer on one of the two images, a second pointer in the shape of a plus sign will be placed at the same position on the second image. This is very useful for assessing the quality of registration between two images.

Suppose that you want to lock image 1 to image 2. You must first select one of the two images, say image 1, by clicking on the image window. You should then select image 2 from the **"Lock to"** submenu in the **Utilities** menu (Fig. 12). The **Lock to** submenu is a dynamic menu because its options change depending on the situation. If you select an image, say image 1, and then look at the **Lock to** submenu, it will only show the images that have the same matrix size as image 1. That is, only those images that are currently loaded in ART and are compatible with image 1 in terms of matrix dimensions are given as options by the **Lock to** submenu. There is no point in providing any other options because they cannot be locked to image 1. For this reason, it is not unusual to see the **Lock to** submenu empty. It simply means that none of the currently displayed images are compatible with the selected image in terms of matrix size.

9.2 Unlocking images

Two images that have been locked together may be unlocked in one of several ways:

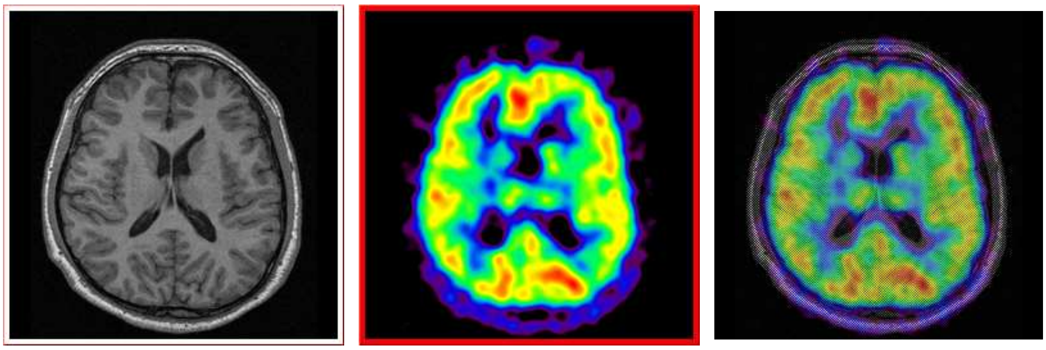
(1) By selecting one of the images and clicking **Unlock** from the **Utilities** menu (Fig. 12).

(2) If one of the images is locked to a third image, its lock with the previous image will be automatically broken.

(3) If one of the images is closed, the lock will break automatically.

9.3 Merging images

ART allows merging two images in order to achieve the fusion effect shown in Fig. 15. In order to merge two images, the first step is to lock them together using the procedure outlined in subsection 9.1. Then select **Merge** from the **Utilities** menu



(a) (b) (c)

Figure 15: (a) Original MRI. (b) PET image resliced to matched the MRI in (a). (c) Merged MRI-PET image.

(Fig. 12). The two locked images will be merged and the result will be displayed in a separate window similar to Fig. 15c. When two images are merged, the following conditions will apply:

(1) Changing the displayed slice on either of the locked images will automatically change the displayed slice on the other image and the merged image.

(2) Changing the colormap of either of the locked images will also change the colormap used for displaying the merged image.

(3) Magnification/demagnification of either of the locked images will automatically magnify/demagnify the other image and the merged image.

(4) Changing the contrast of either of the locked images will also affect the relative contrast in the merged image.

(5) If the mouse pointer is placed on either of the locked images, a pointer in the shape of a plus sign will be placed at the same position on both the second image and the merged image.

If the lock between the two images is broken, the above conditions will no longer be in effect.

10 Registration

This section describes the main function of the ART program, that is, image registration. ART provides two methods of image registration: manual and automatic. They may be started from the **Register** submenu under the **Algorithms** menu (Fig. 16). We will first discuss the manual method.

10.1 Manual registration method

In this section we will describe the necessary steps for obtaining a manual registration. Suppose we want to register image O (the object image) to image T (the target image). That is, to obtain a set of registration parameters such that when image O is resliced, it is in spatial registration with image T.

The manual image registration procedure may be summarized as follows:

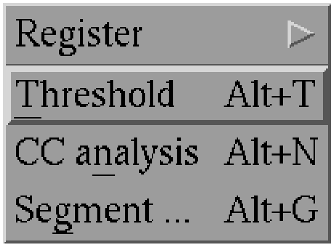


Figure 16: The **Algorithms** menu.

(1) Find the MSP's of object and target images. MSP detection was described in detail in section 6.

(2) Display sagittal slices of the object and target images and select pairs of (corresponding) landmarks on one or more pairs of sagittal slices. Landmark selection procedure is described in the following subsection.

(3) While the sagittal slices are still being displayed, select **Manual** from the **Register** submenu of the **Algorithms** menu (Fig. 16). A window similar to the one shown in Fig. 17 will appear.

(4) Specify the object and target images in this window and click the **OK** button.

ART will compute a set of registration parameters and display them in the main window. The registration parameters thus obtained match the object image to the target image. If you want to obtain the opposite match, that is, to reslice image T to match image O, you must reverse the parameters by clicking **Reverse parameters** from the **Utilities** menu (Fig. 12).

If step (2) of manual registration outlined above is omitted from the procedure, ART will still compute a set of registration parameters. If these registration parameters are applied to image O, it will be transformed such that its MSP is superimposed on the MSP of image T. However, this is not enought to obtain a complete registration between images O and T. Matching the MSP's only reduces the degrees of freedom of the problem from 6 to 3. The remaining 3 degrees of freedom are obtained from the landmark information provided by step (2).

10.2 Landmark selection

In the second step of manual registration (outlined in subsection 10.1), we must select pairs of corresponding landmarks on sagittal slices of both object and target images. ART uses this information to compute a set of registration parameters that matches the corresponding pairs of landmarks as closely as possible (in a least squared error sense). The landmarks are manually selected by the user on sagittal image slices. In order the select landmarks, after MSP detection, display the MSP's of both the object and the target images using **View** from the **MSP** menu (Fig. 8b). Turn on the **Draw** toggle switch on ART's main window. If you now click on a point on one of the displayed MSP planes, it will be identified as a landmark and will be numbered. You must select at least three pair of landmarks for manual registration. However, usually the more landmarks you use, the more accurate the results. Figure 18 shows a pair of displayed sagittal sections and a number of selected landmarks. Note that the

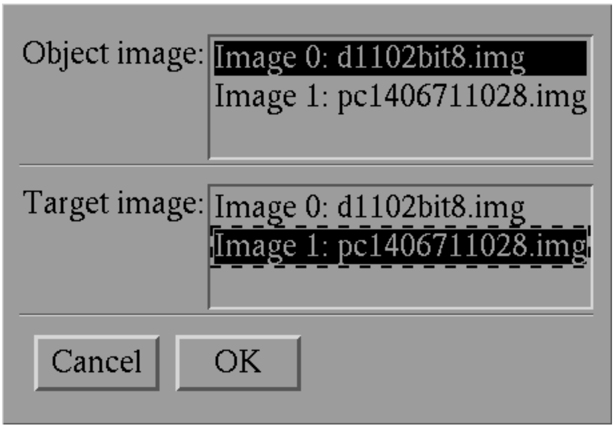


Figure 17: Manual image registration window.

displayed slices in Fig. 18 are not the MSP's but parallel sections distanced 10mm in the positive (x) side of the MSP's. Landmarks may be selected on any number of sagittal slices.

If you make a mistake in placing a landmark, it may be deleted by selecting **Delete** from ART's main window. If you then move the mouse pointer near the landmark, the pointer changes to a "pirate" symbol. You may then delete the landmark by clicking any mouse button. If you press the **Clear** button on Fig. 18, all of the selected landmarks will be deleted.

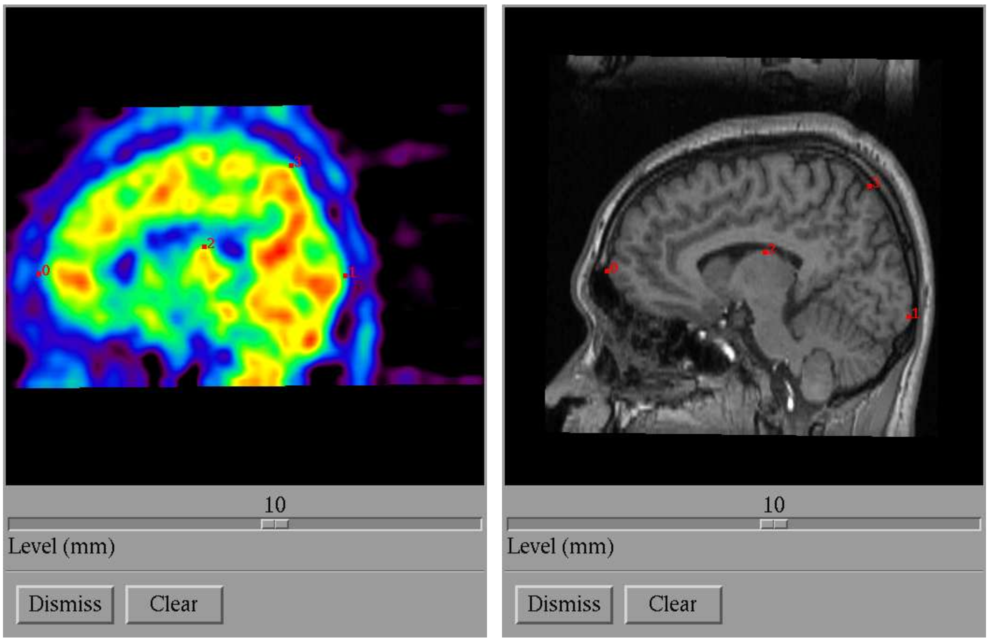
Note that the selected landmarks are in effect as long as the sagittal slices are displayed. If you dismiss the windows in Fig. 18, the landmarks will all be erased. Thus, it is important not to dismiss these window until you have completed the manual registration process.

10.3 Automatic registration method

The automatic image registration algorithm employed in ART is a realization to the algorithm reported by Ardekani *et al.* in "A Fully Automatic Multimodality Image Registration Algorithm," *Journal of Computer Assisted Tomography*, Vol. 19, No. 4, pp. 615–623, 1995. To start this algorithm, select **Automatic** from the **Register** submenu of the **Algorithms** menu (Fig. 16). A window similar to the one shown in Fig. 19 will appear. Select the anatomical (CAT or MRI) image and the functional image (PET or SPECT) and click **OK**. A window similar to the one shown in Fig. 20 will appear informing you that an automatic registration process is in progress. You may cancel the operation by clicking **Cancel** in this window.

The automatic image registration algorithm always makes the anatomical image the target and the functional image the object. Therefore, the resulting registration parameters match the object image to the target image. That is, if the functional image is resliced using the registration parameters, it will be in spatial registration with the anatomical image. In order the reslice the anatomical image to match the functional image, the parameters must first be reversed using the **Reverese parameters** option from the **Utilities** menu (Fig. 12).

Note that the window shown in Fig. 19 allows the user to set several parameters before starting the registration process. In most cases, the default parameters (shown



(a) (b)

Figure 18: (a) PET sagittal slice. (b) MRI sagittal slice. Four pairs of landmarks are selected for manual registration.

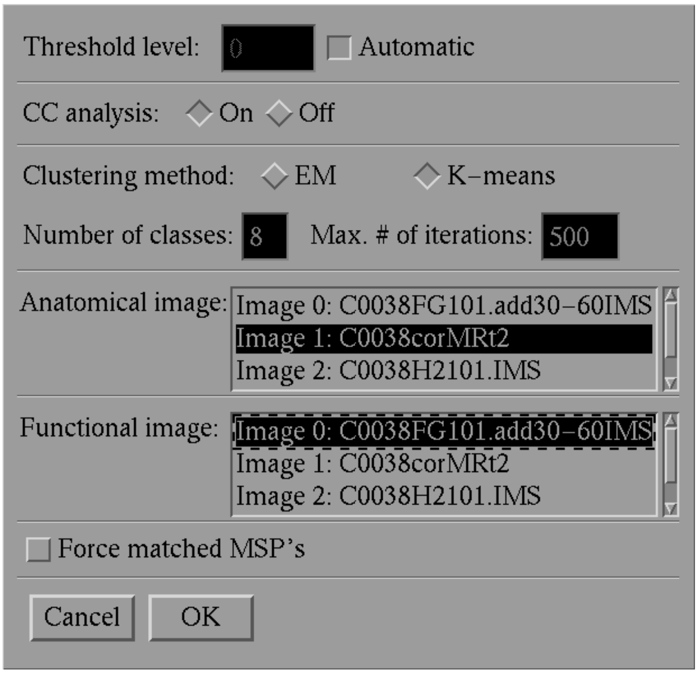


Figure 19: The automatic image registration parameters window.

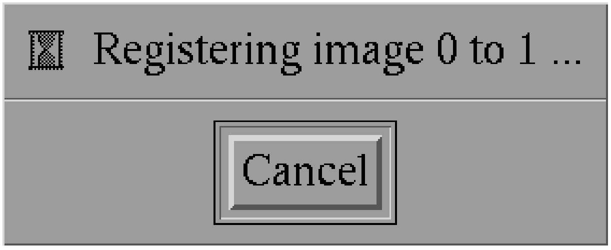


Figure 20: This window indicates that an automatic registration process is in progress. In this case, the target is image 1 and the object is image 0.

in Fig. 19) will achieve a good result and the user does not have to change any of the parameters. In the following subsections, we will explain these parameters in detail.

10.4 Thresholding

The automatic registration algorithm uses a threshold value to separate the head/brain pixels from the background pixels in the anatomical image. This value can be found automatically by histogram analysis or specified manually. As shown in Fig. 19, by default, ART will find the threshold value automatically. However, it is also possible to turn off the **Automatic** switch in Fig. 19 and specify a threshold value manually in the **Threshold level** text area.

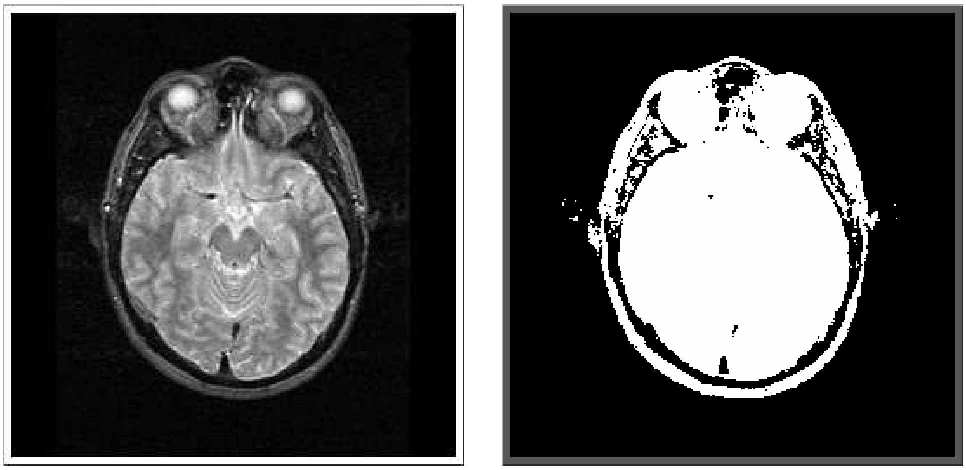
But during automatic registration, how do we know that ART has found a proper threshold value automatically? To answer this question, ART allows the user to apply the automatic threshold selection process as a separate step in order to evaluate its result. To apply automatic threshold selection, click **Threshold** from the **Algorithms** menu. The selected image will be thresholded and the result will be shown in a newly created image (Fig. 21). In addition, a window similar to one shown in Fig. 22 will appear showing you the automatically selected threshold level. In this example, the automatically selected threshold level equals 176.

A satisfactory threshold level is one that outlines the head/brain contour in the anatomical image. For example, the threshold level of 176 which produced the result shown in Fig. 21b is considered to be adequate because in this image the head contour is outlined clearly. If an unsatisfactory threshold level is selected by the automatic routine, the user can find a proper threshold level manually by changing the **Threshold level** slider in Fig. 22. As this slider is changed, the resulting threshold image will be shown in the selected image.

If the automatic threshold selection method does not find a satisfactory threshold and the user obtains the proper threshold manually, the user must specify this in the automatic registration routine by turning off the **Automatic** switch in Fig. 19 and entering the manually found threshold in the **Threshold level** text area.

10.5 Connected Component Analysis (CCA)

After thresholding the anatomical image, by default, the automatic registration method will perform a connected component analysis (CCA) of the resulting binary image. The effect of CCA is shown in Fig. 23. It can be seen that CCA removes the spurious noise around the head and fills the holes inside the head region. ART allows the user to perform CCA independent of the registration process. For this purpose, select the



(a) (b)

Figure 21: (a) Original MRI. (b) Thresholed binary image.

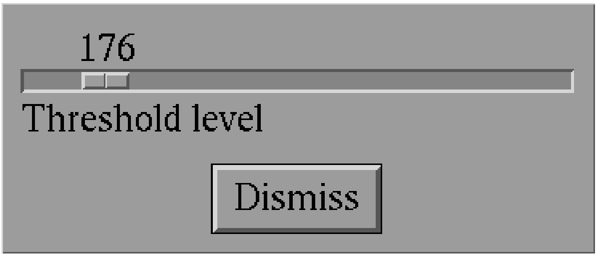


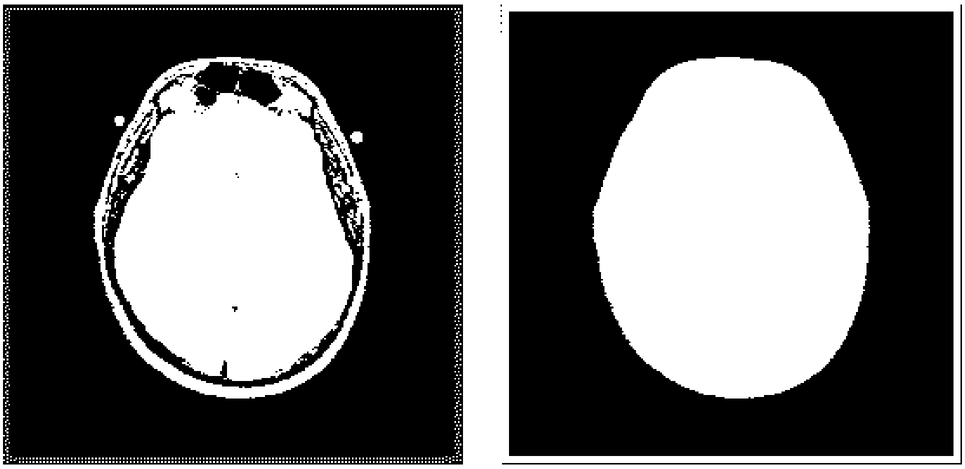
Figure 22: This window shows the automatically selected threshold level. It also allows the user to adjust the threshold level.

image (usually the result of thresholding) and click **CC analysis** from the **Algorithms** menu. Note that CCA does not create a new image. It merely transforms the selected image. As shown in Fig. 19, ART allows the user to turn off CCA during automatic registration. However, in general, CCA helps the registration process and should be kept.

10.6 Clustering

The third preprocessing operation which the automatic registration process performs on the anatomical image is clustering or segmentation. There are two clustering methods in ART, K-means clustering and expectation maximizaition (EM) clustering. The default method in ART is K-means. The EM method has not been tested adequately and should not be used under normal circumstances. Each method requires the user to identify the number of cluster (classes) and the maximum number of iterations the algorithm can run. The default number of classes in ART is 8 and normally does not need to be changed. The maximum number of iterations is not a critical factor.

ART allows the clustering process to run independently from the automatic registration process. In order to run the clustering algorithm, you would normally perform thresholding and CCA first. Then, click **Segment ...** from the algorithms menu. This



(a) (b)

Figure 23: (a) Binary image resulting from thresholding. (b) Result of CCA on image (a).

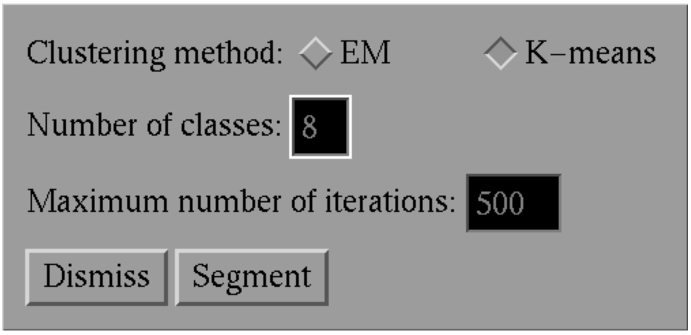


Figure 24: Segmentation parameters window.

will bring up the window shown in Fig. 24. The segmentation options in this window are exactly the same as the ones in the window of Fig. 19 and have already been explained above. Click **Segment** in this window to start the segmentation process. After the segmentation process is finished, the resulting image replaces the selected image.

10.7 Initial registration parameters

ART's automatic registration algorithms searches a six-dimensional parameter space for the "best" set of registration parameters. The search always starts from an initial set of parameters and gradually moves towards the final result. The initial set of parameters from which the search is started is always the current set of parameters shown in ART's main window. In most situations, it will help if this initial starting set is as close as possible to the final answer. Therefore, if the user has any *a priori* information about the registration parameters, they should be entered as the initial parameters before starting the registration process. One method for finding a good set of initial parameters is by performing a rough manual registration as described in subsection 10.1.

10.8 Constrained registration

It was mentioned previously that matching the MSP's reduces the degrees of freedom of the problem from 6 to 3. If the user can locate reasonably accurate MSP's on both the object and target images, then it is possible to constraint the algorithm to match the MSP and only search for the remaining three degrees of freedom. This is achieved by turning on the **"Force matched MSP's"** option in Fig. 19.

10.9 Image reflection

The **Reflect** submenu under the **Utilities** menu allows the selected image to be reflected with respect to xy, yz, and zx planes. The **x-axis** option reflects the selected image with respect to the yz-plane. The **y-axis** option reflects the selected image with respect to the zx-plane. The **z-axis** option reflects the selected image with respect to the xy-plane.

Reflecting images is useful in situations where the object and target images have an obvious mismatch. For example, when the object image slices increase in the superior direction but the target image slices increase in the inferior direction. That is, when the first slice of the object image is the most inferior slice but the first slice of the target image is the most superior slice. In this case, one of the images must be reflected with respect to the xy-plane.