

Institut für Computergraphik und  
Algorithmen

Technische Universität Wien

Karlsplatz 13/186/2

A-1040 Wien

AUSTRIA

Tel: +43 (1) 58801-18601

Fax: +43 (1) 58801-18698

Institute of Computer Graphics and  
Algorithms

Vienna University of Technology

*email:*

technical-report@cg.tuwien.ac.at

*other services:*

<http://www.cg.tuwien.ac.at/>

<ftp://ftp.cg.tuwien.ac.at/>

# TECHNICAL REPORT

## **MammoExplorer: An Advanced CAD Application for Breast DCE-MRI**

Ernesto Coto<sup>\*</sup>, Sören Grimm<sup>†</sup>, Stefan Bruckner<sup>†</sup>,  
Meister Eduard Gröller<sup>†</sup>, Armin Kanitsar<sup>‡</sup>, Omaira Rodriguez<sup>\*</sup>

<sup>\*</sup>Computer Graphics Lab, Central University of Venezuela, Venezuela

<sup>†</sup>Institute of Computer Graphics and Algorithms, Vienna University of Technology, Austria

<sup>‡</sup>Tiani Medgraph, Austria

TR-186-2-05-02 (*revised*)

April 2005

**Keywords:** Breast cancer, Contrast Enhanced MRI, CAD.



# MammoExplorer: An Advanced CAD Application for Breast DCE-MRI

Ernesto Coto<sup>\*</sup>, Sören Grimm<sup>†</sup>, Stefan Bruckner<sup>†</sup>,  
Meister Eduard Gröller<sup>†</sup>, Armin Kanitsar<sup>‡</sup>, Omaira Rodriguez<sup>\*</sup>

<sup>\*</sup>Computer Graphics Lab, Central University of Venezuela, Venezuela

<sup>†</sup>Institute of Computer Graphics and Algorithms, Vienna University of Technology, Austria

<sup>‡</sup>Tiani Medgraph, Austria

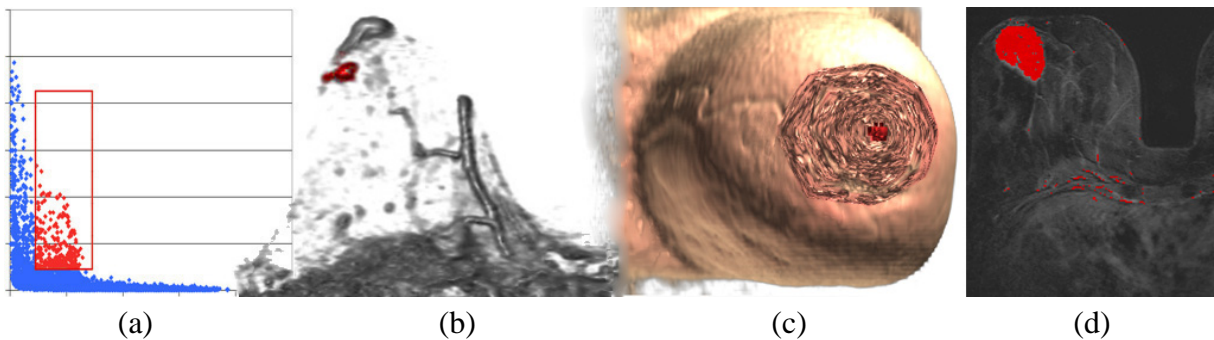


Figure 1: (a) Enhancement scatterplot with brushed points in red, (b) Two-Level volume rendering of a breast highlighting a tumor in red, (c) Importance-driven volume rendering highlighting a tumor in red, (d) 2D slice with red False Color Map.

## Abstract

Breast cancer is the second leading cause of cancer deaths in women today. Although X-ray mammography is regarded as the most widely used method for early detection of breast cancer, the use of Contrast Enhanced MRI (CE-MRI) has gained considerable attention in the past years. Especially, Dynamic CE-MRI (DCE-MRI) considerably improves tumor classification by analyzing the flow of contrast agent within the breast tissue. In this paper we present MammoExplorer, an advanced CAD application that combines advanced interaction, segmentation and visualization techniques to explore Breast DCE-MRI data. In addition, we present a novel graphical representation of DCE-MRI data, new segmentation approaches, and a new way to explore temporal data.

**Keywords:** Breast cancer, Contrast Enhanced MRI, CAD.

<sup>\*</sup>{ecoto|omaira}@opalo.ciens.ucv.ve

<sup>†</sup>{grimm|bruckner|groeller}@cg.tuwien.ac.at

<sup>‡</sup>armin@tiani.com

## 1 Introduction

Cancer is a disease that causes cells in the body to divide and reproduce abnormally without control. These cells may join together to form a mass of extra tissue known as a tumor. A tumor is classified as either benign or malignant. A benign tumor is not cancerous and does not spread to other sites in the body. A malignant tumor is cancerous, it can penetrate, destroy healthy body tissues, and travel to other parts of the body. Breast cancer refers to a malignant tumor that has developed from breast cells. Excluding cancers of the skin, breast cancer is the most common cancer among women, accounting for nearly one of every three cancer cancers diagnosed in the US [17], and one case of every eight cases in Europe [1]. The best way to fight breast cancer is early detection.

The most widely used radiological means of early detection of breast cancer is X-ray Mammography, where low doses of radiation produce X-rays, obtaining high-quality 2D images of the breast tissue on a film. Although X-ray Mammography is standard in clinical

practice, it has shown lower sensitivity to certain high risk cases [5], dense breasts cases [15], or breast implants [9]. Therefore, other imaging techniques are applied to detect the cancer, such as Magnetic Resonance Imaging (MRI), Ultrasound, Tomosynthesis, etc [16]. The use of MRI in breast imaging (termed MR mammography or Breast MRI) has gained considerable attention in recent years, especially for high risk cases [5].

Breast MRI is a non-invasive procedure that uses magnetic fields and radio waves to produce digital images of internal breast tissue. Each study comprises hundreds of images, cross-sectional in all three directions (side-to-side, top-to-bottom, front-to-back), which are then viewed by a radiologist. Usually, Contrast Enhanced MRI (CE-MRI) is performed, where a contrast agent is used to enhance the tissue structure to assist in determining the location of the disease. In general, MRI collects signals from water protons. The presence of a contrast agent creates magnetic fields approximately one thousand times stronger than those corresponding to water protons, therefore it appears brighter than regular tissue in MRI images, as shown in Figure 2. Breast tumors grow their own blood supply network once they reach a certain size; this is the only way they can continue to grow. As the contrast agent is usually absorbed by tissues containing a high vascularity, possible tumors are highlighted. Both benign and malignant tumors absorb the contrast agent.

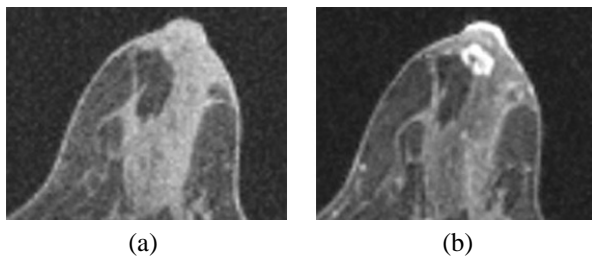


Figure 2: CE-MRI of a patient's breast (a) before contrast (b) after contrast application.

In order to classify the possible tumors, the flow of the contrast agent is analyzed. Usually, several MRI scans are acquired once the contrast agent is introduced into the person's body. This process is called Dynamic CE-MRI (DCE-MRI). These postcontrast scans are subtracted from a precontrast scan in order to highlight suspicious regions, as shown in Figure 3.

Taking all the subtracted scans a contrast agent flow chart can be generated. For each specific location within the breast a curve is generated showing the enhancement of contrast agent over time with respect to the

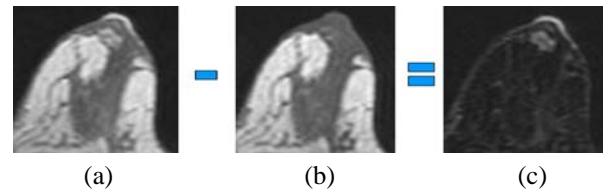


Figure 3: Subtraction of MRI scans to highlight enhanced areas. (a) postcontrast image (b) precontrast image (c) subtraction a-b.

postcontrast scans. Such a curve is referred to as time-signal intensity curve [6] (also called time-signal curve). For breast lesions, different major types of time-signal curves can be identified, as shown in Figure 4. Time 0 corresponds to the precontrast scan.

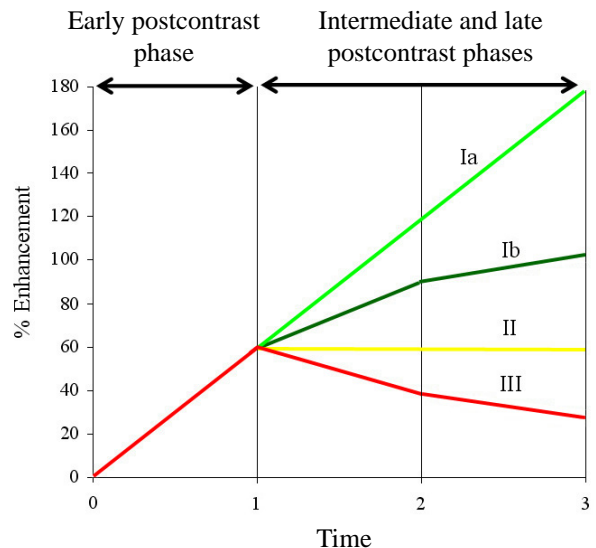


Figure 4: Schematic drawing of the time-signal curve types.

These curves are classified according to the flow of the contrast agent over time. Curves showing low or none increase in the early postcontrast phase correspond to healthy tissue and they are not studied. Three major types are distinguished: continuous and reduced increase, no change in intensity, and decrease in the intermediate and late postcontrast phase. Type Ia correspond to a continuous increase. The Type Ib corresponds to a reduced increase due to saturation effects. Type I curves are referred to as persist. Type II shows no change in intensity and it is, therefore, referred to as plateau. Type III corresponds to a decrease in the intermediate and late postcontrast phase and is, therefore, referred to as washout.

According to a study of over two hundred sixty-six breast lesions performed by Kuhl et al. [6], Type I curves are rated to be indicator of a benign lesion, Type II are rated as suggestive of malignancy, and Type III are rated as indicative of a malignant lesion.

It is also possible to classify tumors according to their shape [13]. Tumors with sharp margins and an abrupt interface with the surrounding tissue are benign in most of the cases. Classic breast cancer has an irregular boundary as they invade the surrounding tissue producing an ill-defined boundary.

Nowadays, hospitals performing Breast MRI exams have a fixed workflow to analyze patient studies. Often, once the data is acquired, a technologist manually creates subtraction images at the MRI workstation, and then sends them to the radiologists workstation for examination, see Figure 5.

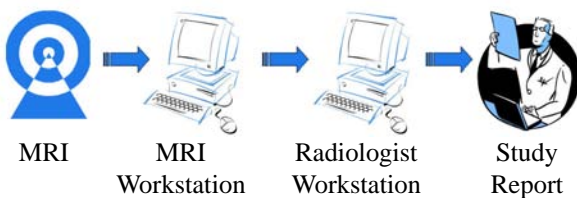


Figure 5: Breast MRI study analysis workflow.

The radiologist manually goes through all the slices and searches for suspicious regions. This is a very time consuming task, as these regions can be very small. It is quite likely to miss suspicious regions due to the human factor. Once a suspicious region is detected the radiologist has to analyze this region. This is also done manually by specifying a region of interest (ROI) within this region. For this ROI a corresponding time-signal curve is computed and then the region is classified. This process has to be repeated for every suspicious region, and therefore the examination usually takes around 30-40 minutes. This kind of examination requires constant attention of the radiologist over a very long period of time. Furthermore, a radiologist performs several studies during a day which can lead to fatigue and therefore to inattention during the examination.

We propose to overcome this problems by exploring Breast DCE-MRI data using a sophisticated combination of interaction, segmentation and advanced visualization techniques. In this paper, we present MammoExplorer, the prototype of a new application to explore Breast DCE-MRI data combining brushing [8] with multiple linked views [2], advanced volume rendering techniques [10][18], 3D seeded region-growing algorithms [14], and a new graphic representation of DCE-

MRI data, called enhancement scatterplot. A novel approach to explore DCE-MRI data is also proposed.

The presentation of our approach is subdivided as follows: Section 2 surveys related work, Section 3 presents an overview of MammoExplorer, Section 4 presents our segmentation approaches, Section 5 describes how visualization of the data according to ROIs is performed, Section 6 presents different ways to explore DCE-MRI data, Section 7 presents the new suggested workflow that radiologists can follow using MammoExplorer. Finally, conclusions and future trends of work are presented.

## 2 Related Work

Carruthers et al. [4] presented a system to identify, process, visualize and quantify lesions from Breast DCE-MRI volumes, based on time-signal curves. The system takes as input five consecutive CE-MRI volumes. The user has to specify a time-signal curve that roughly reflects the type he is looking for. Alternately, a user may pick a few voxels central to a lesion, and examine their time-signal curves. This requires that the radiologist has to find the suspicious regions manually. According to the similarity to this mean curve a confidence degree of malignancy is assigned to each voxel and displayed in different intensities of red. By this approach the user is limited to detect only lesions with time-signal curve behavior which is approximately similar to the specified mean curve. Thus, if there is a different type of tumor, with a different time-signal curve, within the breast the radiologist could miss this type. Another approach by Carotenuto et al. [3] employs time-signal curves of DCE-MRI volumes to automatically display a False Color Map (FCM). Each type of curve is mapped to a different color. All regions corresponding to the different types of curves are displayed simultaneously, however, it is a discrete mapping as opposed to a smooth transition between the different kind of curves. Therefore it is not possible to distinguish uncertain regions from certain regions, which can lead to a wrong interpretation.

We propose a novel approach which is capable of overcoming these limitations, by allowing a more intuitive exploration, several kinds of presentations of the data in 2D and 3D, advanced region-growing and segmentation features. All components are integrated with advanced linking and brushing of the data in a highly interactive way.

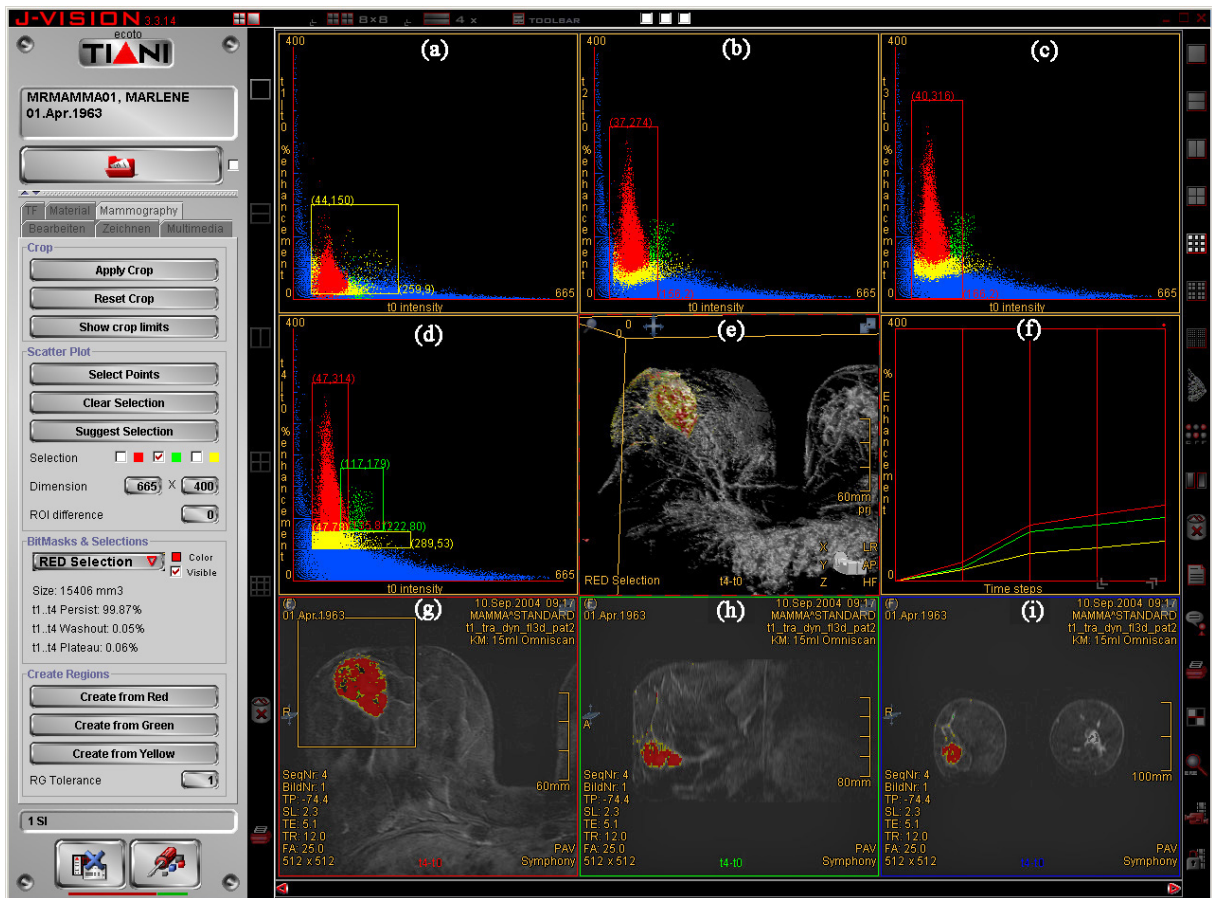


Figure 6: MammoExplorer working with a DCE-MRI sequence of five scans. (a)-(d) Enhancement scatterplots for subtracted volumes  $t_1-t_0$ ,  $t_2-t_0$ ,  $t_3-t_0$  and  $t_4-t_0$ . (e) 3D view. (f) time-signal curve view. (g)-(i) axial, sagittal and coronal views.

### 3 Overview of MammoExplorer

MammoExplorer is integrated into a commercially available medical workstation, shown in Figure 6. It requires as input a DCE-MRI sequence containing at least two timesteps. The first volume in the sequence is a precontrast timestep, and the others are postcontrast timesteps.

Once MammoExplorer is started it automatically computes, for every postcontrast timestep in the input sequence, its subtraction from the precontrast timestep. Afterwards MammoExplorer opens a user panel and as many enhancement scatterplot views as subtracted volumes were calculated, one 3D view, one time-signal curve view, and three cross-sectional views (sagittal, coronal and axial).

The enhancement scatterplots serve as an interface for a sophisticated segmentation algorithm. They allow the

radiologist to brush the Breast DCE-MRI data in a very intuitive way. In addition, using the panel or the cross-sectional views, the radiologist can activate an enhanced 3D region-growing algorithm which automatically creates new ROIs.

Every interesting region can be explored with the traditional slice-through approach using the cross-sectional views, but we have incorporated a 3D view that is able to display advanced volume renderings of the data and the ROIs. A time-signal curve view is also available for radiologists that are used to this method. All views are linked to each other for effective correlation of all the data.

In the following sections we describe how to accomplish segmentation, visualization and exploration of DCE-MRI data, and how all the views of MammoExplorer are linked to each other.

## 4 Segmentation of DCE-MRI Data

It is natural for the radiologist to try to separate suspicious breast tissue from the normal tissue. In computer graphics this is accomplished by segmenting the data. MammoExplorer can segment the DCE-MRI data using enhancement scatterplots, cropping the DCE-MRI data or applying a sophisticated 3D region-growing algorithm.

### 4.1 Enhancement scatterplots

An enhancement scatterplot for Breast DCE-MRI data shows the positive percentage of enhancement of a subtracted volume with respect to the precontrast timestep intensity values. We call  $t_0$  the precontrast timestep and the postcontrast timesteps are called  $t_1, t_2, t_3$  and so on, in the order they were acquired. The relative enhancement of  $t_0$  intensities with respect to timestep  $t_i$  intensities is calculated according to (1) as in [6]. Pixels in  $t_0$  with intensity zero are not taken into account, since they are not part of the breast area. In Figure 7 an example enhancement scatterplot is shown, where a  $(x,y)$  point indicates that a voxel with intensity  $x$  in  $t_0$  had an enhancement of  $y\%$  by the time  $t_1$  was acquired.

$$\%Enhancement(t_i - t_0) = \frac{(t_i - t_0)x100}{t_0} \quad (1)$$

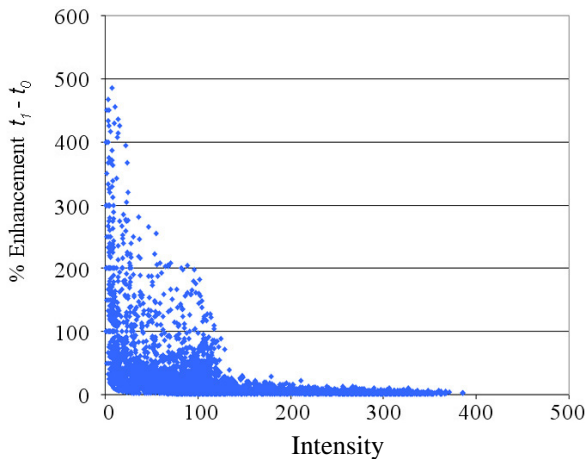


Figure 7: Enhancement scatterplot for subtracted volume  $t_1-t_0$ .

An enhancement scatterplot is designed in such a way, that it allows brushing by means of a selection box, where all points inside the box are accounted for selection. Up to three independent selection boxes are supported, distinguished by different colors, as shown

in the enhancement scatterplots of MammoExplorer in Figures 6(a) to 6(d). A selection box allows the user to perform a *two-level thresholding*, since it specifies a range in both axis of the scatterplot. This kind of brushing allows to categorize the data into three major types, as shown in Figure 8.

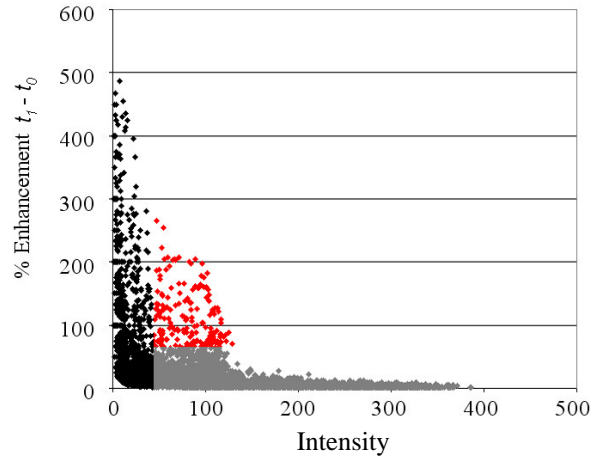


Figure 8: Enhancement scatterplot for subtracted volume  $t_1-t_0$ , divided into three categories.

Black points correspond to voxels which have a low intensity value. These voxels are most likely air or noise and they tend to show big changes in intensity value, due to noise during image acquisition. Grey points correspond to voxels which have small changes in intensity, due to noise, moving artifacts or the low absorption of contrast agent. Red points correspond to voxel with high enhancements, mostly attributed to a high absorption of contrast agent. Radiologists are interested in the red category, but the criteria to set the boundaries between these three categories vary from one study to another, and therefore the placement of the selection boxes has to be interactive. A possible criterion to place the selection boxes on the scatterplots is explained in Section 7.

One enhancement scatterplot displays information about one subtracted volume. Displaying multiple enhancement scatterplots, one for each subtracted volume, allows to display *temporal information*. Thus, the flow of the contrast agent from one timestep to the next can be studied. In order to support brushing over time we propagate the selection made in one enhancement scatterplot to the other enhancement scatterplot. Brushed points are highlighted in all views, as shown in Figures 6(a) to 6(d). In the case where several enhancement scatterplots have a selection box a logical AND is performed on the selections. The radiologist selects only

those points common to all selections, and therefore refines the selection taking into account information in the other timesteps. This way the user can brush a set of voxels from the dataset, and study the flow of the contrast agent through all acquired timesteps.

Once the user has made a selection using the enhancement scatterplots, all the other views are immediately updated, as explained in Section 5.

## 4.2 Cropping the DCE-MRI volume

In general, every enhancement scatterplot shows the information of all the subtracted volume. We also allow to "crop" the volume and focus the attention on a specific part of the breast. After cropping, the size of the data is reduced and the signal-intensity scatterplots display less data, allowing a more detailed selection. In Figures 6(g) and 15(g), the user has cropped the volume drawing a rectangle in the axial view. Once the user has cropped the DCE-MRI volume, all the other views are immediately updated. Figure 9 shows the effect of the cropping in the 3D view.

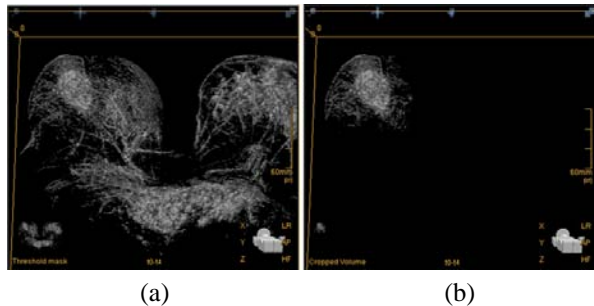


Figure 9: Cropping the DCE-MRI volume (a) before cropping (b) after cropping.

## 4.3 3D time-signal region-growing

Another way to specify a ROI is to start a 3D Seeded Region-Growing (SRG) algorithm [14] from the points brushed on the scatterplots. When segmenting intensity volumes, a 3D SRG algorithm usually grows a 3D volume choosing voxels with similar density around the seed. For MammoExplorer, we have extended the algorithm to grow a volume of neighboring voxels with similar pattern of enhancement. Two voxels have a similar pattern of enhancement if both of them are brushed as explained in Section 4.1. MammoExplorer allows the user to set the seed of the SRG algorithm using the cross-sectional views, as shown in Figure 10. The user

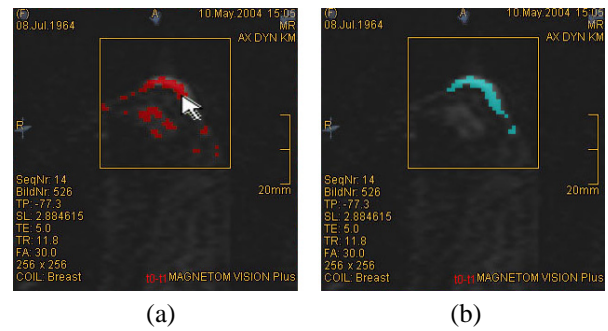


Figure 10: Activating 3D region-growing algorithm (a) selecting the seed (b) new ROI.

can set a minimum region size in order to avoid the creation of very small regions.

Furthermore, we also support automatic connected-component growing based on the selected points in the enhancement scatterplots. This is accomplished by considering each selected point as possible seeding point. Once a selected point belongs to a connected component it is no considered as seeding point anymore. Finally each connected component represents a potential tumor.

Once the user has segmented a new ROI, all the other views are immediately updated, as explained in Section 5.

## 5 Visualization of DCE-MRI Data

The radiologist needs to know the spatial location, shape and extent of the ROIs. Therefore he needs to visualize the brushed regions in the context of the patient's breast. MammoExplorer provides the radiologist with 2D and 3D views of the data and the ROIs. We display three cross-sectional 2D views of the data with False Color Maps (FCMs) highlighting the brushed areas. Advanced volume rendering techniques are used to provide the radiologist with a 3D view of the breast and the ROIs.

### 5.1 False Color Maps

It is easy to obtain the spatial position of the brushed pixels. We just quickly browse the subtracted volumes looking for pixels with the characteristics specified by each selection box. Once the spatial locations are computed, it is possible to create a False Color Map for each brushed area, that is superimposed on to the 2D cross-sectional views the radiologist is familiar with: sagittal (side-to-side), axial (top-to-bottom) and coronal (front-to-back).



Figure 11 shows the brushing of all regions with an enhancement over 60% immediately after contrast injection, linked with an axial view of the subtracted volume  $t_1 - t_0$ . Since multiple FCMs can overlap each other, an interaction method to show and hide any brushed region is provided in the panel. The radiologist can also slice-through the 2D cross-sectional images, in order to visualize the FCMs in all the MRI image stack.

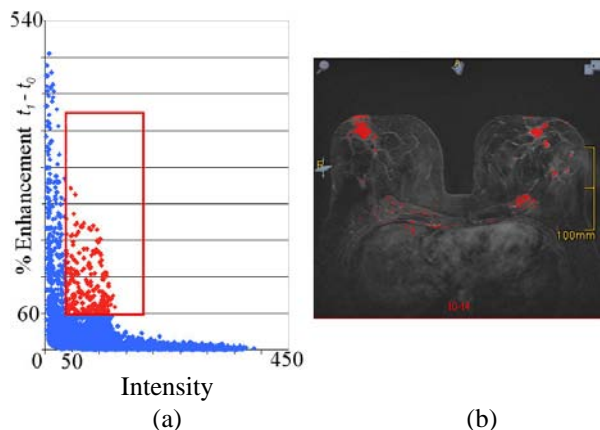


Figure 11: Linking a single selection in a  $t_1 - t_0$  enhancement scatterplot. (a) brushed selection (b) axial view with FCM.

## 5.2 Volume Rendering

Since MRI is a 3D imaging technique, it is possible to display a volume rendering of the subtracted volume to visualize the shape of the lesion in an efficient timely manner. Maximum Intensity Projection (MIP) [11] can be used, or Composite Ray Casting (CRC) [7] as shown in Figure 12.

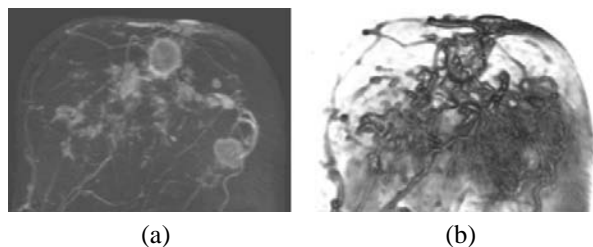


Figure 12: Volume Rendering of the breast (a) MIP (b) CRC.

We propose the creation of a bitmask volume for every brushed ROI in the enhancement scatterplots, so a Two-level Volume Rendering [10] can be applied. This allows to selectively choose the most suitable technique

for depicting each ROI within the data, while keeping the context of the breast visible at a reasonable level. Figure 13 shows three brushed tumors and the breast rendered using CRC but with different transfer functions. Notice how the ROIs are visualized together inside a semi-transparent breast, providing a focus+context visualization. A wide range of different rendering methods can be applied once the bitmasks are created.

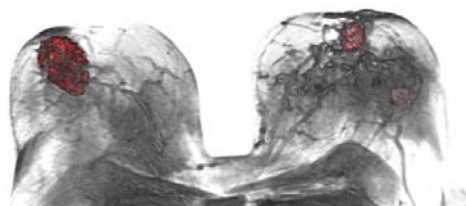


Figure 13: Two-level volume rendering showing two brushed tumors on a patient's breast.

Importance-driven Volume Rendering [18] can also be applied, giving more importance to the radiologist's selection and less importance to the rest of the tissue. This also produces focus+context volume visualization of the radiologist's selection, as shown in Figure 14. In addition, *automatic importance assignment* can be done, automatically brushing areas in the breast showing more than one specific relative enhancement in the early post-contrast phase.

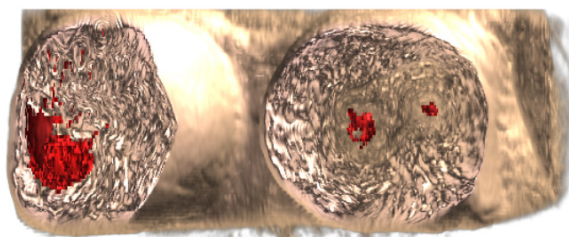


Figure 14: Importance-driven Volume Rendering highlighting tumors shown in Figure 13.

## 5.3 Exploration of DCE-MRI data

MammoExplorer provides three ways to explore the temporal DCE-MRI data. The most traditional way is using a time-signal curve chart, shown in Figure 6(f). A mean time-signal curve is computed for every brushed region. All mean curves are displayed simultaneously in the time-signal curve view, so the radiologist can compare the enhancement pattern of every ROI. Another traditional approach is to observe all subtracted volumes to

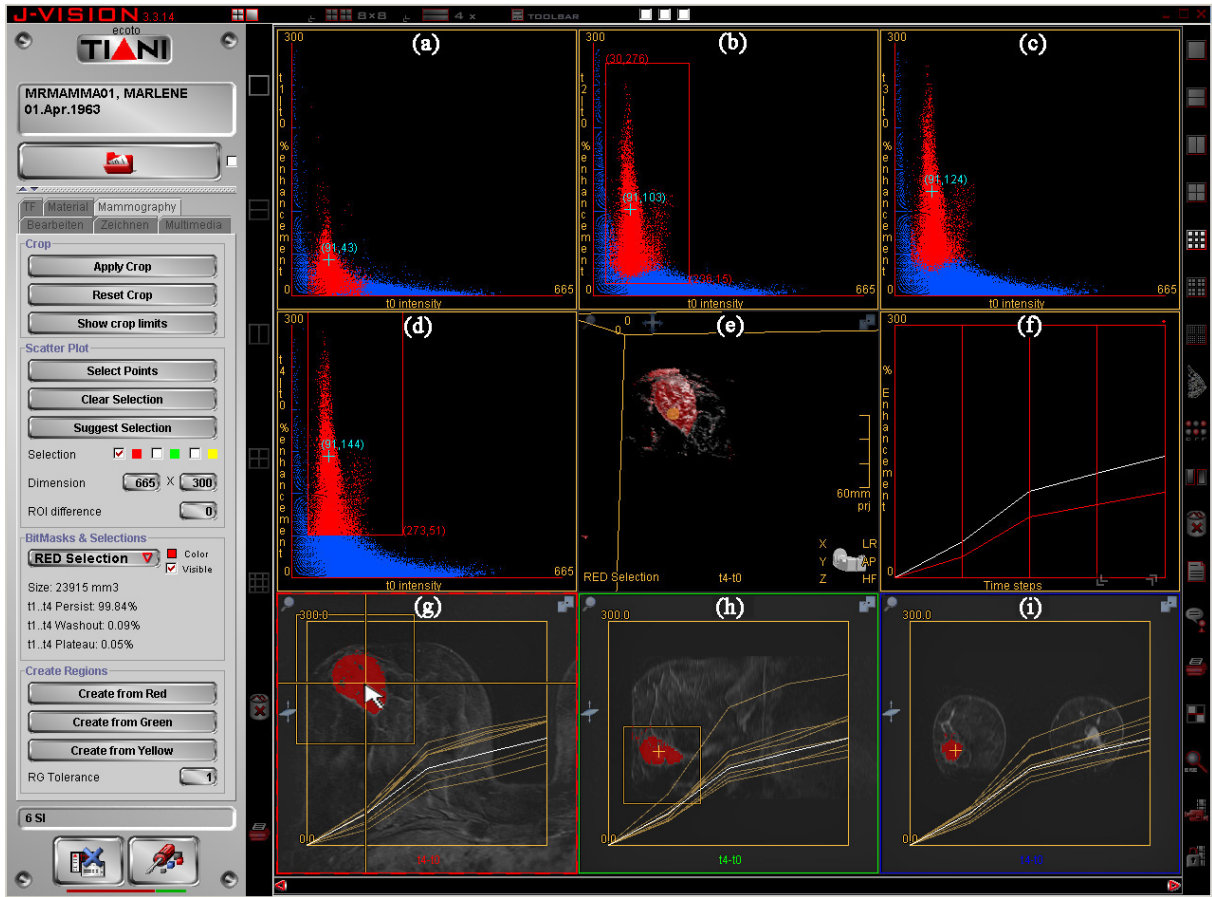


Figure 15: The user picked a voxel using view (g), triggering the update of all views. The position of the voxel is indicated in yellow in views (e), (h) and (i). A blue small cross shows the intensity and the enhancement of the picked voxel in views (a)-(d). In (f) the time-signal curve of the voxel is shown in white, along with other curves. In views (g)-(i) the time-signal curve of eight neighboring voxels are shown.

have a visual feedback on the enhancement of the suspicious areas. MammoExplorer automatically computes every subtracted volume, so the user can visualize any of them in the 3D and 2D views. Since every enhancement scatterplot is directly related to its correspondent subtracted volume, the user can easily specify which volume to display by clicking in the enhancement scatterplot of the subtracted volume he would like to visualize, immediately changing the volume displayed in the 3D and 2D views.

As the third way, we propose a novel exploration mode connecting all the different components of our approach, as shown in Figure 15. MammoExplorer allows the radiologist to pick a voxel in an arbitrary slice on any of the cross-sectional views. Then, information about the picked voxel is shown in all the views. On each enhancement scatterplot, the intensity and percentage of enhancement of the picked voxel is displayed, there-

fore indicating the flow of contrast agent in the picked voxel. In the 3D view the location of the picked voxel is displayed, therefore providing the radiologist with the 3D spatial location of the picked voxel within the breast tissue. In every cross-sectional view, including the one where the user activated the exploration mode, the position of the picked voxel is displayed. Also the time-signal curves of eight neighboring pixels around the picked pixel are shown. In another view, the time-signal curve of the picked voxel is displayed, along with the mean time-signal curves of the brushed regions.

## 6 Suggested Workflow

Comprehensive interpretation of Breast DCE-MRI studies requires answering the following essential questions:

- Is there an enhancement showing a lesion?
- Where is the lesion located?
- What is the lesion's size?
- Has the tumor travelled to other parts of the breasts?
- Is the tumor benign or malignant?
- If the patient was already under treatment, did the tumor change ?

In order to answer these questions using MammoExplorer, we suggest a new workflow, different to the workflow shown in Figure 5. In order to explain the steps in our workflow, we take as an example a sequence of five timesteps, of a 42 year old woman with suspicious lesions in the left breast. Once the radiologist load the DCE-MRI data, MammoExplorer displays the nine views shown in Figures 6 and 15.

The first step of a radiologist is to identify if there is an enhanced lesion or not. In the study of Kuhl et al. [6], a relative signal intensity increase of more than 60% on the first postcontrast image is considered indicative of breast cancer. It is very easy with our method to perform a selection like this by using a box to specify such a range in the first enhancement scatterplot, correspondent to subtracted volume  $t_1-t_0$ , as shown in Figure 11(a). Notice that the radiologist can select pixels with intensity higher than a specific intensity, in order to skip the pixels in the background. In Figure 11(a) we have avoided pixels with intensity lower than 50. The radiologist can also press the button "Suggest Selection" in the panel, so MammoExplorer automatically draws a default selection box based on these criterions. Besides the criterions of Kuhl et al. [6], the radiologist can brush any desired range of enhancements within the enhancement scatterplot. In addition, the radiologist can use the exploration mode to visualize in the enhancement scatterplots what is the enhancement rate of the suspicious region and the surrounding pixels. Afterwards he could make a selection that includes the lesion he would like to examine.

If a suspicious lesion is found, in the following step the radiologist uses it to find out the location, the size and the type of tumor he is dealing with.

With MammoExplorer, the location of the tumor is visualized immediately after the radiologist has brushed a region using the enhancement scatterplots, since these are automatically linked to the 2D and 3D views. The radiologist can immediately visualize the location and

extent of the tumor in every slice using the cross-sectional views, shown at the bottom of Figures 6 and 15. At the same time, a focus+context volume rendering of the tumor and the breast is shown in the 3D view, always highlighting the tumor, so the radiologist can visualize the 3D location of the tumor inside the breast.

The size of the tumor is also automatically computed and shown in the 3D view. Since for every ROI a bit-mask volume is created, the estimated volume of a lesion is calculated multiplying the number of active voxels in the bitmask by the size of a voxel in the data. This computation is fast and is shown immediately after the user has identified the suspicious lesions. In addition, the cross-sectional views are used to display the longest diameter of a lesion within a specific slice, that can also be useful for surgery planning.

The next important step is to classify the lesion as benign or malignant. This is usually done studying the changes in the enhancement through time and taking a look at the shape of the tumor. With MammoExplorer the user immediately visualize the shape of the tumor using the 3D view and he can also study the changes in the enhancement using the enhancement scatterplot. The radiologist just have to add selection boxes in more than one scatterplot. A selection like the one shown in Figure 16, restricts the selection to pixels with a steady increase in the first two postcontrast timesteps, and also with an increase over 60% in the early postcontrast phase. This indicates the lesion is benign.

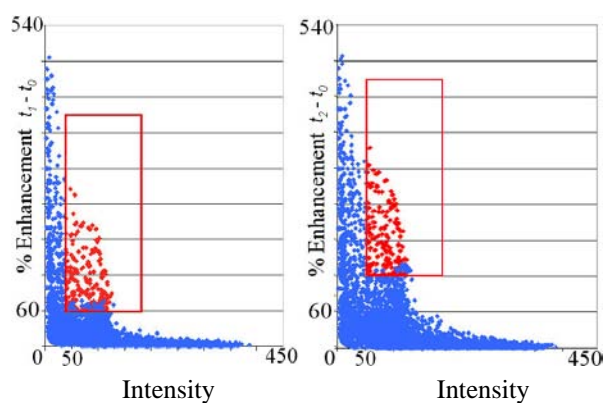


Figure 16: Restricting selection adding linked selection boxes for subtracted volumes  $t_1-t_0$  and  $t_2-t_0$ , searching for a benign tumor.

A selection like the one shown in Figure 17, restricts the selection to pixels with an increase of more than 60% in the early postcontrast phase, but with an increase below 60% in the late postcontrast phase. Selected points are shown in red. This would indicate that the lesion is ma-

lignant, but in this case the selection is empty since no point in our example matches both constraints.

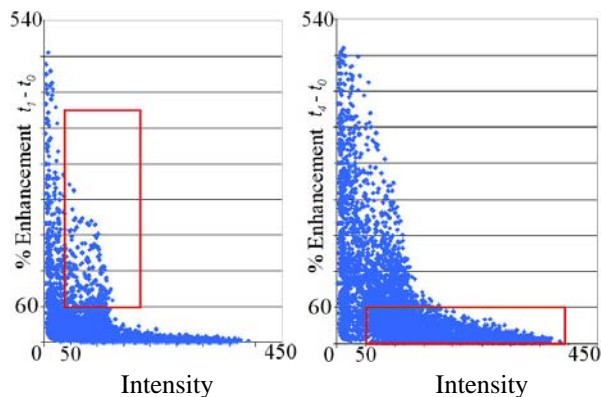


Figure 17: Restricting selection adding linked selection boxes for subtracted volumes  $t_1-t_0$  and  $t_4-t_0$ , searching for a malignant tumor.

In addition, the mean time-signal curve of the suspicious lesion is shown in the time-signal curve view, for radiologists used to type of display. All this information is shown automatically and immediately after the user has identified the suspicious lesions. Using the time-signal curve view the radiologist can also compare the different mean curves for every brushed ROI. The panel also shows, for every ROI, the percentage of voxels in the ROI with a persist, washout and plateau pattern of enhancement.

If the tumor is found to be malignant, then the next step of the radiologist is to find out if the tumor has spread to other parts of the breast. The enhancement scatterplots show information of the entire volume. If the tumor has travelled to other tissues around it, a radiologist's selection highlights all of those regions that are interesting, even if they are not connected.

If the patient has to undergo treatment, then more examinations are required after a certain period of time in order to measure the patients response to treatment. It can be measured according to tumor size, but changes in tumor vascularity occur earlier than shrinkage of tumor mass. This lead to an earlier assessment of response or failure of a particular drug. The study on the flow of contrast agent is a study of tumor vascularity. New DCE-MRI sequences are acquired after a given period of time in order to compare the results with the ones obtained before the treatment started. This allows to evaluate the patient's response to treatment.

Since using our approach a radiologist can compute the size and contrast flow characteristics of the ROIs and even study the shape of the lesion. Therefore he can

produce a report based on the BI-RADS<sup>TM</sup> [12] Atlas terminology. Later on, the radiologist can take this report and compare it with a report of a study performed a given period of time after the treatment started. In this way he obtains a quantified view of the patient's response to therapy.

## 7 Conclusions and Future work

MammoExplorer is a sophisticated combination of interaction, segmentation and advanced visualization techniques. We hereby demonstrated that is possible to explore Breast DCE-MRI data combining brushing and linking, advanced segmentation approaches and state-of-the-art volume rendering techniques. We proposed and proved the usefulness of the enhancement scatterplots as a new graphic representation of DCE-MRI data, and we also presented a novel approach to explore temporal data. We strongly believe that our application allows the radiologist to perform a more in-depth exploration of the breast and considerably reduces the usual workflow time. We hope this will lead to a more accurate diagnosis. In the future we will use MammoExplorer to conduct a medical case study with a large population of women.

## 8 Acknowledgements

The work presented in this publication has been funded by the ADAPT project (FFF-804544). ADAPT is supported by *Tiani Medgraph*, Vienna (<http://www.tiani.com>), and the *Forschungsförderungsfonds für die gewerbliche Wirtschaft*, Austria. See <http://www.cg.tuwien.ac.at/research/vis/adapt> for further information on this project.

The DCE-MRI datasets used are courtesy of the MR-Institut, Univ.-Klinik für Radiodiagnostik Innsbruck, Austria and the KH Lainz MRT Wien, Austria.

## References

- [1] P. Boyle and J. Ferlay. Cancer incidence and mortality in europe, 2004. *Annals of Oncology* 2005, 16(3):481–488, March 2005.
- [2] Andreas Buja, John Alan McDonald, John Michalak, and Werner Stuetzle. Interactive data visualization using focusing and linking. In *VIS '91*:

- Proceedings of the 2nd conference on Visualization '91*, pages 156–163. IEEE Computer Society Press, 1991.
- [3] L. Carotenuto, M. Ercolani, R. Passariello, C. Catalano, F. Pediconi, and F. Venditti. Software tool for computer aided diagnosis of breast cancer in contrast enhanced mr sequences. In *EuroPACS-MIR 2004 in the Enlarged Europe*, pages 361–364. P. Inchingolo and R. Pozzi-Mucelli, September 2004.
- [4] W. Carruthers, K. Subramanian, and J. Brockway. Interactive detection and visualization of breast lesions from dynamic contrast enhanced mri volumes. *Computerized Medical Imaging and Graphics*, 28(8):435–444, December 2004.
- [5] M. Kriege, C. Brekelmans, C. Boetes, P. Besnard, H. Zonderland, I. Obdeijn, R. Manoliu, T. Kok, H. Peterse, M. Tilanus-Linthorst, S. Muller, S. Meijer, J. Oosterwijk, L. Beex, R. Tollenaar, H. de Koning, E. Rutgers, and J. Klijn. Efficacy of mri and mammography for breast-cancer screening in women with a familial or genetic predisposition. *New England Journal of Medicine*, 351(5):427–437, July 2004.
- [6] C. Kuhl, P. Mielcareck, S. Klaschik, C. Leutner, E. Wardelmann, J. Gieseke, and H. Schild. Dynamic breast mr imaging: Are signal intensity time data useful for differential diagnosis of enhancing lesions? *Radiology*, 211(1):101–110, April 1999.
- [7] M. Levoy. Efficient ray tracing of volume data. *ACM Transactions on Graphics*, 9(3):245–261, July 1990.
- [8] John Alan McDonald, Werner Stuetzle, and Andreas Buja. Painting multiple views of complex objects. In *OOPSLA/ECOOP '90: Proceedings of the European conference on object-oriented programming on Object-oriented programming systems, languages, and applications*, pages 245–257, New York, NY, USA, 1990. ACM Press.
- [9] D. Miglioretti, C. Rutter, B. Geller, G. Cutter, W. Barlow, R. Rosenberg, D. Weaver, S. Taplin, R. Ballard-Barbash, P. Carney, B. Yankaskas, and K. Kerlikowske. Effect of breast augmentation on the accuracy of mammography and cancer characteristics. *Journal of the American Medical Association*, 291(4):442–450, January 2004.
- [10] L. Mroz, H. Hauser, G. Bischi, and M. Eduard Gröller. Two-level volume rendering. *IEEE Transactions on Visualization and Computer Graphics*, 7(3):242–252, 2001.
- [11] L. Mroz, H. Hauser, and M. Eduard Gröller. Interactive high-quality maximum intensity projection. *Computer Graphics Forum*, 19(3):C341–C350, August 2000.
- [12] American College of Radiology. *Breast Imaging, Reporting, And Data System: BI-RADS Atlas*. American College of Radiology, fourth edition, 2003.
- [13] R. Rangayyan, N. El-Faramawy, J. Desautels, and O. Alim. Measures of acutance and shape for classification of breast tumors. *IEEE Transactions on Medical Imaging*, 16(6):799–810, December 1997.
- [14] C. Revol-Muller, F. Peyrin, Y. Carrillon, and C. Odet. Automated 3d region growing algorithm based on an assessment function. *Pattern Recognition Letters*, 23(1-3):137–150, 2002.
- [15] F. Sardanelli, G. Giuseppetti, P. Panizza, M. Bazocchi, A. Fausto, G. Simonetti, V. Lattanzio, and A. Del Maschio. Sensitivity of mri versus mammography for detecting foci of multifocal, multicentric breast cancer in fatty and dense breasts using the whole-breast pathologic examination as a gold standard. *American Journal of Roentgenology*, 183(4):1149–1157, October 2004.
- [16] A. Smith, P. Hall, and D. Marcello. Emerging technologies in breast cancer detection. *Radiology Management*, 26(4):16–24, August 2004.
- [17] American Cancer Society. Breast cancer facts and figures 2003-2004. ACS Web site, 2004.
- [18] I. Viola, A. Kanitsar, and M. Eduard Gröller. Importance-driven volume rendering. In *Proceedings of IEEE Visualization 2004*, pages 139–145. H. Rushmeier, G. Turk, J. van Wijk, October 2004.