ELSEVIER

European Journal of Ultrasound 7 (1998) 225–230

EUROPEAN JOURNAL OF ULTRASOUND

Educational report

SONOSim3D: a multimedia system for sonography simulation and education with an extensible case database

Hans-Heino Ehricke *

Polytechnical University of Stralsund, Medical Imaging and Computer Graphics Lab, Fachhochschule Stralsund, Fachbereich Elektrotechnik und Informatik, Zur Schwedenschanze 15, D-18435 Stralsund, Germany

Received 5 September 1997; received in revised form 15 January 1998; accepted 7 February 1998

Abstract

This paper addresses the problem of sonography education and training. A method and software package for ultrasound simulation are presented. The latter is based on standard PC technology and allows graphical interaction with a virtual patient and transducer. The most essential component is an extensible case database with various cases from different clinical disciplines. A case consists mainly of a 3D image dataset, sonographically acquired from a patient or a healthy subject. It represents an anatomical region which may be investigated. Furthermore, a method for the geometric registration of the data volume of a new case with the model of the virtual patient is described. This enables the arbitrary extension of the case database.

Keywords: Ultrasonography; Clinical; Training; Multimedia; Simulation; 3D imaging

1. Introduction

The impact of ultrasound as a diagnostic imaging modality has undoubtedly grown during recent years. The practice of ultrasound is expanding in many areas of clinical medicine and as a consequence there is an increasing request for education and training (Bolondi, 1997). Particularly in many areas of Eastern Europe sonographic equipment is becoming available for a widespread use. Education and training are prerequisites for the successful application of ultrasound technology in practice.

A variety of medical training systems based on multimedia and computer graphics have been described in the literature. They range from arthroscopy and endoscopy simulation (Göbel,

* Tel.: +49 3831 456674; e-mail: ehrick@fh-stralsund.de/www.micg.et.fh-stralsund.de

0929-8266/98/$19.00
PII S0929-8266(98)00033-0

1996; Davis et al., 1996) to surgical and neurosurgical training (Gillner et al., 1997; Ehricke and Laub, 1990). Grunst et al. (1995) present a sonography simulator for echocardiography. They use a puppet as a physical model of a patient together with a transducer dummy operated by the trainee. Position and orientation of the dummy related to the patient model are registered by an electromagnetic localization system. The information is used to locate the image plane within a 3D echocardiographic dataset. The section images are reconstructed and displayed on a computer monitor in realtime. The primary drawback of the method is it's need for special and expensive equipment to be installed on a computer system. This hampers the widespread use of the system for training purposes. Another disadvantage is the limitation of the image database to only one cardiac dataset.

This paper presents a sonographic trainingsimulator for use on a standard personal computer including an extensible case database. The latter demonstrates various anatomic regions and pathologies from all clinical disciplines, where ultrasound is applied as an imaging modality. The successful application of ultrasound in clinical medicine requires substantial knowledge and skills, regarding especially (1) the mental integration of section images into the 3D reality, and (2) the interpretation of greytone patterns in terms of organs and pathological phenomena.

The primary goal of the approach presented in this paper is to support training of these skills without the necessity of having available an ultrasound apparatus together with a variety of healthy subjects, or of patients resp. with different pathologies. A trainingsimulator is described, which is operated interactively based on a graphical computer, a digital patient model and a realtime visualization software.

2. Graphical-interactive simulation

The *SONOSim3D* system, which is described here, is based on a simple idea: 3D sonographic image datasets are used for the reconstruction of arbitrary slice images. These are interactively defined by operating a graphical transducer model within a virtual scene on a computer monitor. Thus, a trainee may graphically simulate an ultrasound examination on a virtual patient, viewing slice images, which are reconstructed and displayed on the monitor in realtime. The approach comprises the following elements (Fig. 1):

- a computer graphics system for display and manipulation of a patient and a transducer model,
- reconstruction algorithms and software for the generation of slice images from a 3D image data volume,
- a case database on CD-ROM including case descriptions and corresponding image volumes,
- a digital patient model consisting of graphical surface data (patient surface, organ surfaces) and 3D image volumes (Computed Tomography and Magnetic Resonance datasets, pathology slices from the Visible Human project).

During a training session the user may choose from a variety of different cases, sorted by anatomical region and pathology. After case selection, the corresponding image dataset is loaded from CD-ROM into the computer's main memory. The volume data of the patient model are also made available in the main memory. The graphical surface data of the patient model are displayed on the monitor as a skin surface representation. This provides a virtual scene, in which a transducer model is manipulated interactively. Position and orientation of the transducer related to the patient coordinate system are registered. This information defines image slices within the case as well as the patient volume. The ultrasound slice image is reconstructed from the case volume in realtime and displayed on the monitor. In order to ease the anatomic interpretation, the trainee may switch between different display modes:

- ultrasound (case data),
- CT (patient model),
- MR (patient model),
- pathology (patient model).

In this manner the displayed ultrasound images may be enriched with additional information from

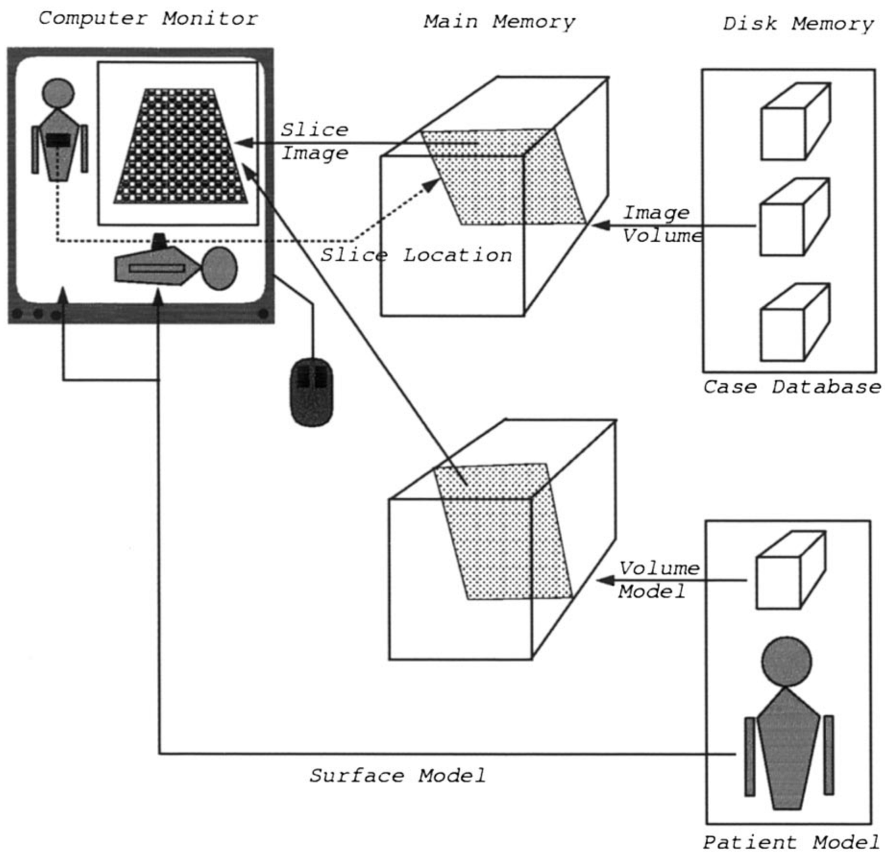

Fig. 1.

anatomically equivalent CT-, MR- or pathology slices.

Fig. 2 shows the user interface of the *SONOSim3D* system. It is based on Windows95/NT and allows graphical interaction using the computer mouse. Transducer operation is performed by picking and moving the transducer model in either the patient front view or the side view. It may be shifted (left mouse button down) or rotated (right mouse button down). The corresponding slice images are reconstructed and displayed with a frame-rate of about 30 images per second. For a better orientation the selected slice is displayed within a voxel cube wireframe. Realtime zoom–pan, contrast–brightness manipulation and switching between curved and linear array transducer geometry are further functions, which may be helpful.

3. Case database

The case database consists of cases from various anatomic regions with different pathologies. A case includes

- a 3D sonographic dataset acquired from a patient or a healthy subject,
- a transformation matrix describing the geometric relationship between the data volume and the patient coordinate system,
- a textual description together with keywords.

The latter is stored within a relational database system allowing a keyword-based search. 3D acquisition may be performed with any of the methods proposed in the literature (Hottier and Billon, 1990). We have used a step-motor system, which rotates the transducer in a sweep-like manner over the body surface. Rotation angles of down to 0.3° and the realtime digitization of the corresponding

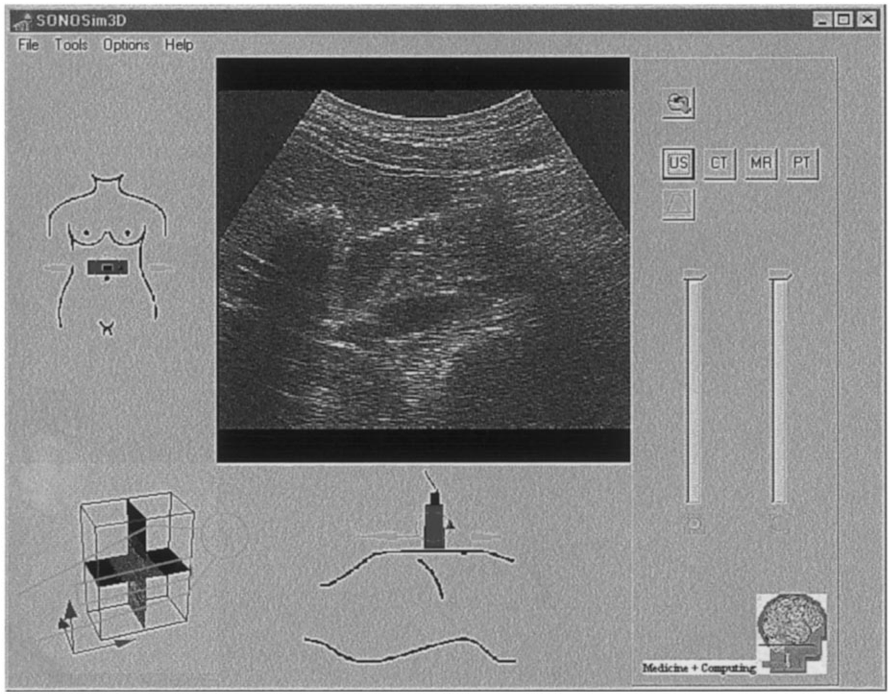

Fig. 2.

ultrasound images allow high-resolution image datasets to be generated within an acquisition time of about 10 s. Transformation matrix and image data are stored on CD-ROM. The image volume has a cartesian coordinate system with three axes u, v, w. The transformation matrix M defines the geometric relationship between the (u, v, w) system and the coordinate system of the patient model (Fig. 3). The patient model is also based on a 3D cartesian coordinate system. It's scheme is as follows:

- x grows from the right to the left side of the patient,
- y grows from anterior to posterior,
- z grows from foot to head.

M defines a rigid transformation including translation, scaling and rotation:

$T(\mathrm{d}x, \mathrm{d}y, \mathrm{d}z)$ where

dx, dy, dz are translation steps

$S(sx, sy, sz)$ where

sx, sy, sz are scaling factors

$R_x(\phi_x)$, $R_y(\phi_y)$, $R_z(\phi_z)$ where

ϕ_x, ϕ_y, ϕ_z are rotation angles around the x, y, z axes

As explained in Foley et al. (1992) a transformation matrix for a homogeneous 3D coordinate system has the form

$$M = \begin{pmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_x \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Each image point (x_i, y_i, z_i) in the patient model may be transfered to the corresponding point in the case volume by

$$\begin{pmatrix} u_i \\ v_i \\ w_i \\ 1 \end{pmatrix} = M * \begin{pmatrix} x_i \\ y_i \\ z_i \\ 1 \end{pmatrix}$$

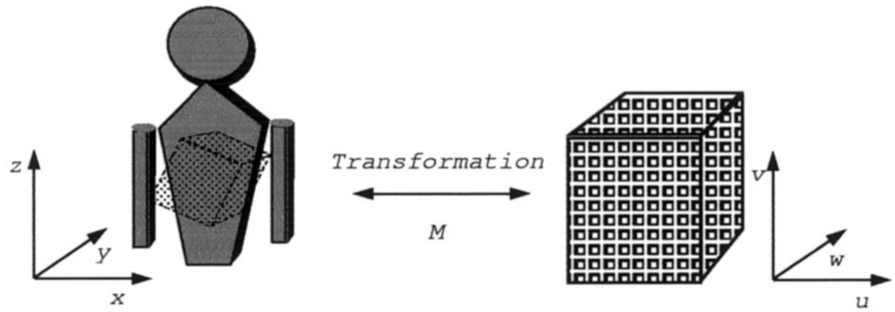

Fig. 3.

Thus an image plane, which is defined interactively by transducer manipulation on the monitor, can easily be transfered to the case volume. The section image then is generated by: (1) construction of a regular pixel grid on the image plane; (2) localization of each pixel within the case volume; (3) bilinear interpolation between grayvalues of neighbouring voxels.

For the resampling of spatially high-resolution 3D data bilinear interpolation is a good compromise between image quality and calculation time. So far, the case database includes only high-resolution datasets. However, the incorporation of low-resolution data might demand other interpolation schemes, such as speckle rendering.

4. Integration of new cases

For the 3D acquisition of ultrasound data several approaches have been described in the literature (Hottier and Billon, 1990). Special-purpose transducers, step-motor systems and electromagnetic registration methods for probe localization are the most important ones. Most systems produce a 3D image volume, which may be imagined as a 3D grid with a greyvalue at each grid point (voxel). The main problem with the introduction of new cases is the definition of the geometric relationship between the coordinate systems of the patient model and the new data volume. As explained earlier, the transformation matrix M describes this relationship. Therefore, we need a method allowing M to be generated.

The patient model possesses volume datasets (CT, MR, pathology), which are based on the x, y, z-coordinate system. One of these is selected for geometric registration with the new case volume. The matching process begins with the interactive definition of anatomic landmarks visible in both image volumes. For this purpose the datasets are displayed on the monitor side by side as slice images. By scrolling through the slice series corresponding anatomic regions may be found and corresponding landmark points defined via mouse input. Each pair of reference points $[(u_i, v_i, w_i), (x_i, y_i, z_i)]$ defines a linear transformation with three equations:

$$u_i = r_{11}x_i + r_{12}y_i + r_{13}z_i + t_x$$

$$v_i = r_{21}x_i + r_{22}y_i + r_{23}z_i + t_y$$

$$w_i = r_{31}x_i + r_{32}y_i + r_{33}z_i + t_z$$

With N point pairs a system with $3{*}N$ equations and 12 unknown parameters is established. With more than 4 point pairs the equation system mostly has more than one solution. Thus an optimization criterium has to be defined:

$$\sum_i [(u'_i - u_i)^2 + (v'_i - v_i)^2 + (w'_i - w_i)^2] \rightarrow \mathrm{Min}$$

That means, the sum of the distances between original and calculated coordinates (u'_i, v'_i, w'_i) is to be minimized. The solution is easily found by linear optimization. Since the definition of point pairs is always due to errors, it is recommendable to use more than 4 point pairs as the basis for registration. Excellent results were achieved with six to ten pairs within calculation times of a few minutes.

5. Discussion

A method and multimedia software package for sonography simulation was described. It is based on the goal of widely making available a cheap and efficient training tool.

It is obvious, that the value of the system very much depends on the quality and extent of the case database. As a prerequisite contributions from a variety of clinicians from different disciplines are needed. Since the technology for 3D acquisition of ultrasound datasets has become available for reasonable prices during the last two years, there is a great chance to establish a comprehensive case database in the near future.

So far, the most exciting field of Doppler sonography has not been addressed in this paper. Since it's clinical relevance has been proven through recent years, a training system should include Doppler training modes and the simulation of dynamic studies. However, the problem arises that dynamic 3D datasets, which are often called 4D data, are extremely dificult to be acquired. Even with high-end acquisition technology the necessary triggering causes acquisition times, which are not acceptable for most patient studies. Therefore, an alternative approach is proposed, namely the simulation of flow on the basis of available 3D datasets. Our preliminary investigations show, that it might be possible to simulate synthetic flow and e.g. the corresponding colour doppler signal after delineation of vascular structures of interest.

Another subject, which deserves special attention and further elaboration of the method, is related to the registration of new cases. In this paper a method for rigid matching of new sonography volumes with the 3D patient model was described. Since anatomic conditions are different with different individuals, the matching result is not exact. That means, that corresponding section images generated from the case dataset and the patient volume may substantially differ with respect to anatomic details, thus impeding the interpretation of the ultrasound data. Non-rigid, so-called elastic matching procedures have to be developed and tested in order to tackle this problem. These may be based e.g. on grayvalue-gradient information, which is instructive especially at organ borders.

The preliminary experience with the described method in the framework of ultrasound courses suggests, that it should provide a practical and useful technique to enhance sonography education.

Acknowledgements

The author is grateful to Volker Pohlers, Polytechnical University of Stralsund, for his kind assistance with the implementation of the described method. I also want to express my gratitude to Dr Spengler, Academic Clinics Stralsund, for his valuable medical input. Further thanks go to MplusC, Stralsund for their allowance to publish Fig. 2.

References

Bolondi L. Message from the president. Eur J Ultrasound 1997;5(2):63–4.

Davis CP, Ladd ME, Romanowski BJ, Wildermuth S, Knoplioch JF, Debatin F. Human aorta: preliminary results with virtual endoscopy based on 3D MR imaging datasets. Radiology 1996;199(1):37–40.

Ehricke HH, Laub G. Integrated 3D display of brain anatomy and intracranial vasculature in MR imaging. J Comp Ass Tomogr 1990;14(5):846–52.

Foley JD, van Dam A, Feiner SK, Hughes JF. Computer Graphics, Chapter 5.6. Matrix representation of 3D transformations. Reading: Addison-Wesley, 1992:213–217.

Gillner S, Schurr MO, Mentges B, Kühnapfel U, Buess GF. VR simulation of a laparoscopic gall bladder removal: evaluation for surgical training. In: Lemke HU, Vannier MW, Inamura K, editors. Computer Assisted Radiology and Surgery. Amsterdam: Elsevier, 1997:565–568.

Grunst G, Fox T, Quast KJ, Redel DA. Szenische enablingsysteme–tramingsumgebungen in der echokardiographie. In: Glowalla U, Engelmann E, de Kemp A, Rossbach G, Schoop E, editors. Auffahrt zum Information Highway. Berlin, Heidelberg: Springer, 1995.

Göbel M. Industrial applications of virtual environments. Comp Graph Appl 1996;16:10–3.

Hottier F, Billon AC. 3D echography: status and perspective. In: Hoehne KH, editor. 3D Imaging in Medicine. Berlin, Heidelberg: Springer, 1990:21–41.