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Technical Aspects of Virtual Liver Resection Planning

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Abstract

Operability of a liver tumor is depending on its three dimensional relation to the intrahepatic vascular trees which define autonomously functioning liver (sub-)segments. Precise operation planning is complicated by anatomic variability, distortion of the vascular trees by the tumor or preceding liver resections.

Because of the missing possibility to track the deformation of the liver during the operation an integration of the resection planning system into an intra-operative navigation system is not feasible. So the main task of an operation planning system in this domain is a quantifiable patient selection by exact prediction of post-operative liver function and a quantifiable resection proposal.

The system quantifies the organ structures and resection volumes by means of absolute and relative values. It defines resection planes depending on security margins and the vascular trees and presents the data in visualized form as a 3D movie.

The new 3D operation planning system offers quantifiable liver resection proposals based on individualized liver anatomy. The results are visualized in digital movies as well as in quantitative reports.

Keywords:
Liver, Tumor resection, Operation planning, Visualization

Introduction

Selection of patients out of the continuum of metastatic tumor progression is the crucial step in liver resection planning. The surgical strategy is dependent on the localization of the liver tumor in relation to the three liver vascular trees. In detail three cornerstones have to be considered in liver surgery:

1. The liver tumor has to be resected completely within sound liver parenchyma.
2. Segments or subsegments of the liver which might get devascularized by liver resection have to be removed as well.
3. Liver function is dependent on sufficient functionally active liver volume.

In patients with multiple liver lesions operation planning is getting difficult as resection planes may cut in a complicated way through the vascular trees leading to devascularized (sub-)segments which have to be removed as well. Distorted anatomy after preceding liver resection and consecutive hypertrophy of the remaining liver parenchyma demands high skills in imagination and operation planning is not quantifiable.

A prediction of absolute or relative rest liver volume has been very difficult and has widely been substituted by simple imagination and rough estimation. Up to now a computer based calculation was not practicable due to missing analysis systems dedicated to tumor resections. A variety of efforts has been undertaken in the past to establish a computer based 3D presentation system for the liver anatomy of individual patients. To our knowledge none of these is available in clinical routine.

The knowledge of the exact three-dimensional relation of the tumor and the vascular trees within the liver decides on the preoperative selection of patients for hepatic resection. Despite low perioperative mortality (0-2%) there is still a high complication rate of up to 35%. Therefore objective and quantifiable selection criteria should be mandatory.

The aim of the developments was to establish a computer based, quantitative, three-dimensional operation planning system in liver surgery. An individualized operation strategy is facilitated which takes into account the anatomic variability of liver architecture in the individual patient. A quantitative operation planning including subsegments will be possible. Patients with multiple liver metastases may benefit by minimizing resection volume without devascularizing sound parenchyma.

The four major goals have been:

- To recognize and separate parenchyma, vessels and tumor.
- To calculate the absolute and relative volumes.
- To recognize and reconstruct the three dimensional vessel trees and describe them by means of a symbolic representation.
- To calculate a resection proposal, which may be modified by the user interactively.

These developments might optimize patient selection as operation planning is getting quantifiable and objective. Complication rates might decrease due to an improved patient selection and by a highly individualized operation planning and resec-

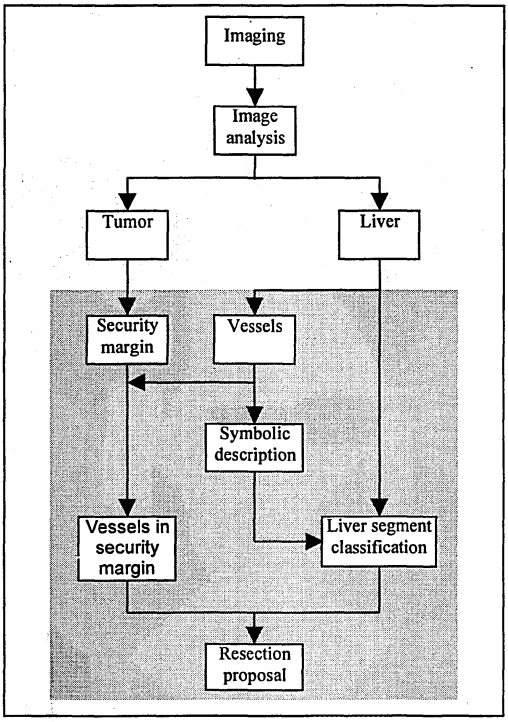


Figure 1 - Data flow in liver resection planning

tion. Besides the advantages for the patient there might be a reduction of the expenditure for intensive care and hospital stay.

Materials and methods

Imaging

CT scans taken from routine diagnostics are used as the input for image processing. According to the actual problem two different methods of contrast agent based techniques may be used:

1. bolus tracking: contrast agent injection using a high pressure pump is triggered by a computer so that the contrast medium reaches the liver just in time when the spiral-CT-scan starts sampling the data from the liver. The cross-section pictures are reconstructed in 2mm slices.
2. CTAP (arterial portal CT): An arterial catheter is introduced into the iliac artery from a skin puncture in the groin. The inflow of the contrast agent into the liver is highly selective, thereby increasing image contrast [1,2]. CTAP is considered to have the highest sensitivity for liver metastases which equals or supersedes intraoperative ultrasound and MRI [3,4]. Therefore CTAP is the most appropriate basis for virtual operation planning in liver surgery.

Image transfer and basic image segmentation

The teleradiology system CHILI supports the data transfer from the CT scanner to the operation planning system which is implemented on a SGI workstation. Various image formats can easily be handled on this platform [5].

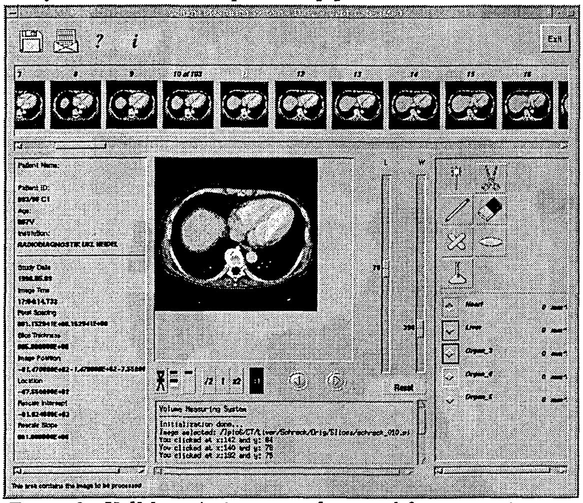


Figure 2 - VolMes - An image analysis tool for interactive segmentation of medical image slices and volumetric measurements

The first version of a system for segmentation and volumetric measurements is completed under the application name VolMes. The main aspects under investigation are the easiness of use, the time needed for the segmentation and the accuracy of the volumetric component. An experienced user needs for segmentation of an object about 20 seconds per slice. Assuming a data set of 50 slices the total time needed for manual preprocessing may be estimated to about half an hour for both objects, liver and tumor. This time needs to be reduced in the near future in order to increase the acceptance of the system in clinical practice. The ergonomic aspects are investigated using an online commenting system integrated in VolMes and by interviewing the users.

Vessel segmentation

CT scans made for routine diagnostics are the input for image processing. By using a contrast agent the vessels appear gray value-enhanced. The segmentation of the vessels can be done automatically by using a standard threshold technique. This step is based on the preceding basic segmentation. Only the voxels assigned to the area of the liver are used as data input. Mainly two pre-processing steps are necessary to obtain good results. After a median convolution an adaptive filtering procedure is applied.

We compared three different thresholding algorithms using a correlation criterion and two different entropy minimizing algorithms. The selection criteria has been the strength of the entropy signal belonging to the threshold of interest. Best results for the liver vessels were achieved using the histogram entropy algorithm described by Kapur [6]. Such a threshold algorithm usually yields more than one possible threshold which are indicated by peaks in the entropy function. A knowledge-based algorithm selects the threshold of interest automatically using the previously obtained information about shape and size of the liver.

Analysis and symbolic description of the vessel tree

In order to divide the liver into its eight segments and to detect devascularized areas an analysis of the intrahepatic blood vessel trees has to be performed. Each of the segments has its own blood supply by a branch of the portal vein and its own drain by an efferent hepatic vein. Thus it is possible to perform the subdivision of the liver on the basis of the branching pattern of one of these vessel trees.

For this purpose a modified region growing algorithm is used which was developed for the detection of bifurcations in vessel trees [7]. The algorithm recognizes the vessels starting from a seed voxel near the porta hepatis and searching for all neighbor voxels which belong to the object. If a branch splits up in two or more subbranches a bifurcation is found. The resulting vessel tree is visualized with several colors for each bifurcation level.

A hierarchical diagram containing nodes and edges is generated where each bifurcation, the seed voxel and all end points are mapped to nodes. The resulting symbolic tree representing the individual vascular anatomy of the liver can be used for an easy interactive analysis and for the subdivision of the liver into its segments.

Connected vessel trees and their separation

In some cases of CTAP and often in the bolus tracking technique the vessel trees of the portal and the hepatic veins are contrasted simultaneously. This leads to pseudoconnections of the portal and hepatic venous trees due to the limited resolution of the CT. Therefore the algorithm described above, might segment parts of both vessel trees and not yield acceptable results. We have developed a new method to separate the two vessel trees.

For this separation we use a similar algorithm to the one described above to trace the structure of the segmented vessels. The symbolic description created with this method is not a tree but a graph, which can describe cycles, too. Each of these cycles has to be removed by severing the graph at the right position. Additionally this separation is based on the thickness of the vessels which must not increase in flow direction. So an overall thickness analysis of every cycle results in optimal severing points. Additionally, areas of potential stenosis are detected.
By using this method the data analysis achieves an increased independence of the acquisition method. Additionally the liver segment classification and the detection of devascularized areas may be based on both vessel trees.

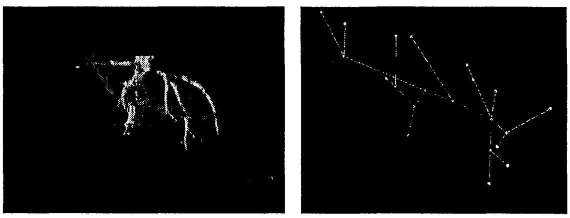


Figure 3 - After the separation of vessel trees (a) the symbolic descriptionof the portal tree may be visualized using VRML (b)

Liver segment classification

Different models have been proposed to determine the eight segments of the liver. Additionally to the classical approach proposed by Couinaud there do exist several models to calculate the segments based on the individual anatomy of the hepatic vessel trees. At the time we use a nearest-neighbor model.

Security margin

The next step in data processing is the calculation of the security margins belonging to each area assigned to the tumor. This means to calculate the distance between every voxel assigned to the sound liver tissue and the areas marked as tumor. This is done by a distance transformation [8]. The binary image of the tumor is used as the input image. The different resolutions (inplane resolution and slice distance) are stored in the image header and have to be considered. We calculate the distances in a data set where the data has been interpolated to equal the inplane resolution of the original data.
The distance transformation results in an image where the security margin can be marked by setting a threshold calculated from the minimum security distance. By combining this information with the image of the segmented vessels those vessels located in the security margin are detected. This is an important information for selecting the operation strategy.

Calculation of the resection index

The combination of information gained by the analysis of the vessel trees and the distance transformation of the tumor results in the possibility of estimating the resection index belonging to a chosen resection strategy. The symbolic description of the vessel trees allows to assign liver areas to certain nodes in the vessel tree supplying these areas. By simulating the actual resection strategy liver areas supplied by injured vessels may be quantified. The volume ratio of resected to total sound tissue is an estimation for the resection index.

Visualization

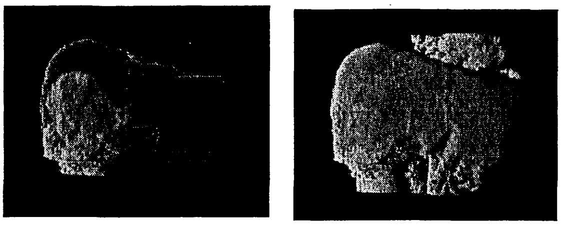
The result of the data analysis is a quantitative analysis containing information about e.g. the volumes of interest as well as a visualization of all interesting regions. The visualizations used in this project are produced with the Heidelberg Raytracing Method Model (HRM). It is a volume-based visualization algorithm which physically models the light-matter interaction in order to create three-dimensional views out of series of image slices. The gray values are interpreted as light absorption coefficients. Two artificial light sources are used which results in realistic representations displaying textured objects. Shadowed objects are a special feature of this algorithm which leads to an increased depth perception. By assigning labels to segmented regions it is possible to visualize these structures in different colors.
Two different ways of visualizing the data are possible. At present an interactive version of the monochromatic HRM and a batch version of a color implementation are available.

Monochromatic visualization

For interactive monochromatic visualization different objects have to be assigned to different gray value ranges. These ranges may be selected interactively, so it is possible to choose the object to be visualized. The position of the observer and the viewing direction may be chosen arbitrarily by moving a wire-frame presented as a graphical overlay.

Color visualization

The color visualizations are produced in batch mode and the results are presented as a digital movie or a video tape..



(a) (b)

Figure 4 - The left image shows the liver and its surrounding organs (a). The transparent liver enables the view on the location of the tumor (b).

The regions belonging to anatomical structures are assigned to "natural colors like the liver (brownish), the vessel trees (red), or the tumor areas (gray). Information gained from the analysis is presented in colors like green for the security margin, yellow for the vessels in the security margin or in future developments blue for the resection proposals.

In principal an arbitrary observer position and viewing direction is possible. In order to standardize the presented visualizations we decided to use only simple rotations for the whole movie. This strategy is generalized and adapts the observers position to the individual anatomical situation.

The visualization consists of five different scenes which contain the important information for surgical planning. In every scene a complete rotation of the liver is performed. The liver is shown transparently in all scenes

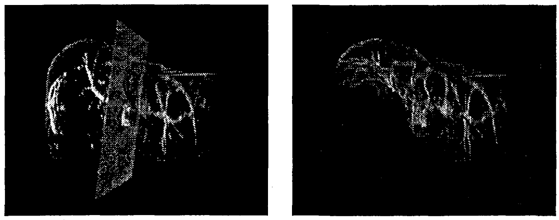
(a) (b)

Figure 5 - The position of the tumor relative to the vessel trees (a). Vessels caught in the security margin are marked (b).

- Firstly the position of the tumor areas are shown in relation to the liver.
- The vessel system is added to the visualized objects. The relative position of the vessel system and the tumor areas are shown.

After its calculation the security margin is faded in as a transparent object. The vessels located in this region are partially hidden.

- The liver is shown transparently in all scenes. Firstly the position of the tumor areas are shown in relation to the liver.
- The vessel system is added to the visualized objects. The relative position of the vessel system and the tumor areas are shown.
- The security margin and the tumor are removed in the next scene and only the transparent liver and the vessel trees are shown. The vessels located in the security margin are colored yellow.
- A resection which is based strictly on the constant security distance is modeled in the last scene of the visualization. The tumor is removed including the security margin. All lesions caused by such a resection strategy are faded in as surfaces.



(a) (b)

Figure 6 - A resection strategy based on the calculated security margin is proposed (a) Future developments will propose real resection strategies (b).

Discussion

Despite the fact that 3D rendering of CT-scans of the liver are carried out for several years no virtual liver resection planning system has been available for use in clinical practice [9]. Quality of patient selection is dependent on a precise quantifiable tumor resection planning. Security margins around the tumor, recognition of vascularly dependent liver (sub-)segments and sufficient functionally active liver rest volume are the cornerstones of resection planning.

We have developed a computer based 3D virtual operation planning system which is ready to go in routine use. It is embedded in the teleradiology system CHILI. So CT scans from the routine (CTAP or bolus tracking enhanced spiral CT scans) can easily be transferred from the devices into our system. We succeeded in decreasing the time needed for the interactive segmentation process of the different tissue structures by designing an ergonomically structured software desktop in addition to refined region growing and edge finding algorithms. Calibrated relative and absolute volume measurements are available from the time of the segmentation process. As the tumor typically does not contribute to the liver functionality the resection index predicts the fraction of rest liver volume over total sound liver parenchyma (without tumor) after resection. So the loss of functionality is mainly caused by the resection of sound parenchyma, which has to be removed because of the relative position of the tumor and vessel trees and the resulting operation strategy. So an important result of the preoperative analysis has to be an estimation of the resection index as an aid for a quantitative prediction of the remaining liver function.

Our 3D analysis system allows to calculate security margins around the tumor and detection of vascularly dependent liver parenchyma which has to be resected as well. This level of operation planning was only possible by 3D modeling of the whole liver. The visualization process is very important for the physician because it leads to three-dimensional perception of the individual anatomy, appreciation of vascularly dependent liver parenchyma and quantifiable resection planning proposals. Different visualization methods show the spatial relation between the tumor, the liver surface and the vessel trees. For this purpose standardized visualizations are calculated which present the complex spatial information in an intuitive way. These visualizations are calculated using the Heidelberg Raytracing Model.
In an advanced version of the described system all vascularly depending liver parenchyma of those vessels which cross or lie within the security margin is resected. The surgeon will be enabled to optimize the operation strategy by using 3D manipulators.
All quantitative and qualitative statements are available the day after the image acquisition at the latest. So the computer-aided image data analysis can be integrated in the operation planning routine. The methods developed for this project are in principle also be applied for operation planning concerning other organs.

Acknowledgements

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