3-D CAROTID ARTERY RECONSTRUCTION FROM DUS IMAGES

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ABSTRACT :

Ultrasonographic techniques have long been employed in noninvasive diagnosis of carotid disease. DUS and other noninvasive imaging modalities, however, provide only 2-D information regarding the arterial pathology. This research concerns the feasibility of non-invasive, photogrammetric and 3-D modelling techniques to form a novel tool for the diagnosis and treatment of carotid artery disease. This tool is based on pre- and post-operative DUS images as well as on post-operative atherosclerotic plaque specimen. The preliminary results indicate that photogrammetric processing of DUS images can lead to modeling, calculations and measurements with excellent data accuracy, since the difference is estimated stenosis is only 0.9%.

1. INTRODUCTION

Each year more than 300.000 Europeans suffer an ischemic stroke. Carotid artery disease is thought to contribute 10-15% of new stroke cases each year. Ultrasonographic techniques have long been employed in noninvasive diagnosis of carotid disease and by now have a significant contribution in the safe and cost effective identification patients that are potential candidates for surgical treatment of severe carotid stenosis. DUS and other either invasive or noninvasive imaging modalities provide 2-D information regarding the arterial pathology. However, intravascular atheromatous pathology is certainly a process that is evolving in space, i.e., is a 3-dimensional process. Atherosclerotic plaque is an abnormal formation that obviously has some volume and alters the geometry of the blood vessel lumen in a more complex way, rather than just reducing its diameter. Across this line of thinking, there are numerous parameters inherent to this 3-D approach, that have in general been understudied and have the potential to better delineate the actual pathologic process and probably contribute significant prognostic information regarding a more efficacious identification of patients at high risk for stroke that will be amenable to surgical intervention.

2. RESEARCH OBJECTIVE

Stroke is currently recognized as the third most common cause of mortality and the leading cause of disability among the developed Western countries. Almost 80% of stroke victims are affected by ischemic stroke, which is often etiologically related to atherosclerotic disease of the carotid arteries. Since attempts to treat ischemic stroke have in general been unsuccessful, prevention remains the most important means of reducing the dreadful impact of stroke on society.

Over the past five years various well designed and conducted studies have conclusively shown that carotid endarterectomy (CEA) can be an effective stroke preventive modality for selected symptomatic and asymptomatic patients with carotid disease. In all these studies tightness of carotid stenosis has emerged as the most important determinant of the necessity and the relative efficacy of the procedure.

Cerebral angiography has traditionally been considered the golden standard technique for the estimation of the degree of carotid stenosis although different criteria for the determination of its severity were used. However, cerebral angiography is an invasive and costly procedure which carries a risk for major morbidity and mortality that even in experienced hands cannot be reduced below 1-2%.(Hankey, et.al., 1990) Furthermore, by focusing on severity of carotid stenosis as the sole predictor of impending ipsilateral stroke, a broader high risk group of patients is identified and patients that will never experience a stroke are included in it. This is especially true for asymptomatic severe carotid stenosis patients most of which will have an indolent clinical course. Consequently, finer and perhaps qualitative selection criteria for defining this high risk group are of crucial importance, keeping in mind that the perioperative mortality and morbidity is 1-5% plus the operative financial burden.

For the past twenty five years various ultrasonographic techniques have been increasingly used for screening purposes in the effort to reliably identify patients with tight carotid lesions. Carotid Duplex Scanning (DUS) has demonstrated a remarkably reliable profile regarding diagnosis of the above mentioned group. Discussion over the issue of whether cerebral angiography can in most part be replaced by DUS grew enormously after the results of the previously mentioned studies became available, but again attention focused almost exclusively on the controversy regarding which is the most reliable means of determining degree of carotid stenosis (Dawson, et.al., 1993). Although this approach reasonably enough deals with a very important parameter of the problem, still it is underestimating other potentially critical aspects.

Due to limitations in current invasive and non-invasive imaging technology carotid artery disease has been traditionally viewed as a rather "flat", two-dimensional pathologic process which restricts either the diameter or the transverse surface of the carotid artery. However, carotid atherosclerotic plaques entail a certain volume which can vary regardless of the severity of the stenosis that it produces. Total volume of the atherosclerotic load consisting the carotid plaque is a rather understudied parameter in regard to the risk of stroke. Changes of carotid plaque volume over time and correlation to development of symptoms might offer novel data for a more efficient characterization of high risk subgroups. On the same line of thinking, volumetric estimations of the different parts that compose the plaque (e.g. echolucent, echogenic etc.) may provide further prognostic possibilities. Finally, instead of using merely the presence or absence of a plaque ulcer to predict clinical outcome, total ulcerated area estimates may prove better predictors of distal embolization of thrombotic material formed on the plaque and consequently, of the risk for ipsilateral artery-to-artery embolic stroke.

The above outlined qualitative requirements necessitate the development of new sophisticated techniques which by processing of DUS images will provide both geometric and semantic-qualitative information. This kind of information is quite important in our effort to prevent stroke and avoid unnecessary carotid operations.

Among the other, potentially important, carotid plaque determinants of the risk for cerebrovascular complications are morphology and composition of the atherosclerotic plaque (Nikolaides, 1995). Atherosclerotic plaque ulceration, confirmed either pathologically or angiographically, has been repeatedly shown to increase the risk of stroke (Belcaro, et.al., 1993). More recently, Transcranial Doppler (TCD) sonography has revealed that detection of transient microembolic signals is more likely when carotid plaques are ulcerated. Ultrasonographic carotid plaque characteristics, such as echogenicity and echolucency of the plaque and morphologic parameters such as heterogeneity, irregularity of its surface and the presence of calcification have all been suggested as other critical determinants of stroke risk. In addition, certain histologic findings, such as intraplaque hemorrhage, foam cells, necrotic cores and speckled calcifications tend to be more frequent in areas of the plaque with an echolucent ultrasonographic appearance. Finally, the issue of stenosis can be alternatively approached by looking at the actual residual lumen and not at the percentage of stenosis. In his landmark 1961 study on carotid disease C.M.Fisher was the first to propose that a residual lumen diameter of less than 1.5 mm best predicts a high probability of ipsilateral stroke. Very recently the Mass. General Hospital group has reached similar conclusions (Suwanwela, et.al., 1996).

Photogrammetric techniques have long been used for mapping and 3-D reconstruction of objects through measurements of image coordinates on overlapping images. Photogrammetric procedures are based on highly accurate image coordinate measurements on two or more overlapping images. Subsequently, based on the image taking geometry, sensor orientation is estimated. Finally, provided that the measured points sufficiently describe the mapped surface, the 3-D coordinates of the measured points are estimated, thus producing a 3-D reconstructed object. Under the assumption that the images are in digital form (as is the case with DUS), it is anticipated that the photogrammetric techniques will exhibit the potential to fulfill all previously outlined requirements.

Therefore, the anticipated objectives of the proposed project are :

1. *The research on the feasibility of non-invasive, photogrammetric and 3-D modelling techniques to form a novel tool for the diagnosis and treatment of carotid artery disease. The development of this novel tool will be based on pre- and post-operative DUS images and on pathologic examination of atherosclerotic plaque as well.*
2. *The procedures should go beyond the 2-D angiographic information, produce 3-D mappings and vessel reconstruction, providing geometric and qualitative information such as :*
   - *Degree of carotid stenosis.*
   - *Residual lumen of the carotid artery.*
   - *Volume of the atheromatic plaque.*
   - *Volume of the atheromatic plaque components.*
   - *Quantitative and qualitative characteristics of the plaque.*
3. *Morphology and volume of the plaque ulceration.*

4. *The methodology should be automatic or semi-automatic, reducing to as little as possible the human intervention, in order to produce homogeneous, measurable and predictable accuracy regardless the human expertise.*

5. *The procedures should have build-in capabilities for expansion to on-line operation.*

3. METHODOLOGY

3.1 Duplex Studies

The examination is performed with the patient in the supine position and the head slightly rotated to the contralateral side from the one under study. The hand held probe is initially positioned over the proximal common carotid artery (CCA) at the lower part of the neck. By moving the probe distally and scanning in various planes, the examiner identifies the distal segment of the CCA, the carotid bifurcation (BIF), the internal carotid artery (ICA) and the external carotid artery (ECA).

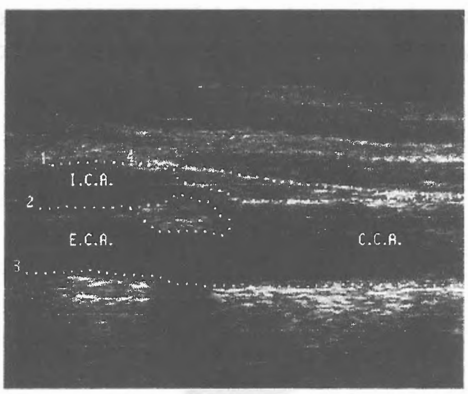

Figure 1: DUS scanning in longitudinal plane

The vessels are scanned in both transverse (Fig. 2) and longitudinal planes (Fig. 1) and for the latter an anterior oblique and posterior oblique approach is been used. Scanning at standard transverse planes, i.e. at the level of the proximal and distal end, at the mid-portion of the atherosclerotic plaque and at 1 cm below the BIF into the CCA is performed.

Using B-mode real-time imaging as a map, the examiner is placing the Doppler sample volume parallel to the stream of flow in the center of the vessel and sets the Doppler angle of insonation at approximately 60 degrees, or less. Maximum peak systolic velocities (PSV) and end-diastolic velocities (EDV) from the ICA stenosis site and also from the CCA is recorded and ICA/CCA PSV ratios is calculated. Arterial stenoses measurements are been made based on changes of blood flow velocities at the vessels of interest. Standard criteria proposed by Zwiebel are been used (Zwiebel, 1992).

3.2 Operation

The eversion CEA technique is employed. Briefly, this involves oblique cutting of the ICA at the bifurcation site and removal of the plaque via an eversion maneuver. A classic endarterectomy of the ECA and CCA follows the completion of the ICA endarterectomy and the atherosclerotic plaque specimen is obtained.

Compared to classic CEA technique, the eversion CEA technique it has been shown to be superior in regard to restenosis rates. Furthermore, the fact that this particular technique enables us to remove intact the atherosclerotic plaque from the carotid artery is an even greater advantage regarding the aim of the study.

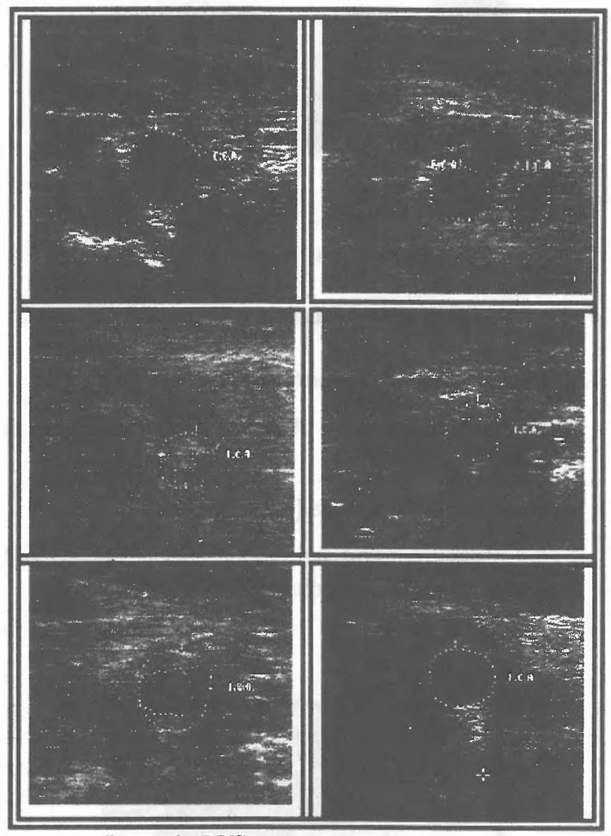

Figure 2: DUS scanning in transverse planes

3.3 Pathologic examination of the plaque

The endarterectomy specimen from each patient is been evaluated pathologically and will be used as the real data "ground truth".

The pathological examination consists of the evaluation of the macroscopic and microscopic features of each endarterectomy specimen, that is ulceration, hemorrhage, thickness of the fibrous cap, presence of necrotic core, thrombus material, calcifications, lipid, smooth muscle cells, elastic fibers, cholesterol crystals, lymphocytic infiltration, as well as the compartment of dividing cells. The appropriate histochemical or immunohistochemical stains are been used.

Each specimen is sectioned at 1-2mm (Fig. 3) intervals and each section is embedded in paraffin, except for 3 sections per specimen, that are been frozen for special stains. From each paraffin block several sections are cut with a microtome, so that the whole group of the following stains are been used : Haematoxylin and eosin, Masson's trichrome stain, Verhoeff's elastica, Oil-red, Von Kossa, PTAH, Immunohistochemical stains (factor VIII and Ulex Europeus, smooth muscle actin, PCNA and Ki-67, UCHL1 and L-26).

Figure 3: Microscopic image of dyed section

3.4 Photogrammetric processing

3.4.1 Description of the material

- specimen of the plaque obtained after the operation (Fig. 4)
- preoperative DUS images (Figs. 1, 2)
- digital photographs of the plaque slices (Fig. 5) and their microscopic dyed counterparts (Fig. 3)

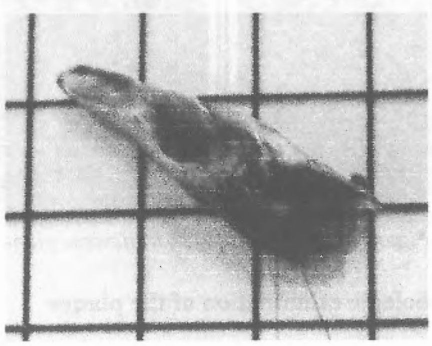

Figure 4: specimen of the plaque

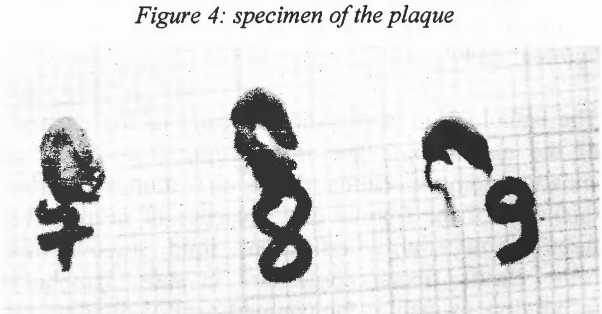

Figure 5: Digital images of plaque slices

3.4.2 Description of the method

The plaque specimen has been previously sliced every 2mm or 1mm, depending on the level of detail. Each slice has been photographed with the Kodak DCS420 digital camera, with pixel size of 9 μm , in order to map the interior of the plaque. Also, the whole plaque has been photographed before the slicing in order to map the exterior, which corresponds to the artery surface.

The two surfaces of each slice have been photogrammetrically reconstructed, brought to the same reference frame and put together using computer 3-D modeling techniques. Thus the whole plaque is been modeled. This is considered as the "ground truth" for which the degree of the stenosis is being calculated.

The result of this step is a 3-D wireframe computer model on which one can measure coordinates, areas and volumes, can perform "walk-throughs", and can obtain horizontal and vertical cross-sections of the model at any desired location. For a more realistic result the computer model can be visualized as a solid object either by utilizing shading and lighting algorithms (e.g. ray tracing) or by draping the model with the photographic image of the plaque (Fig. 6).

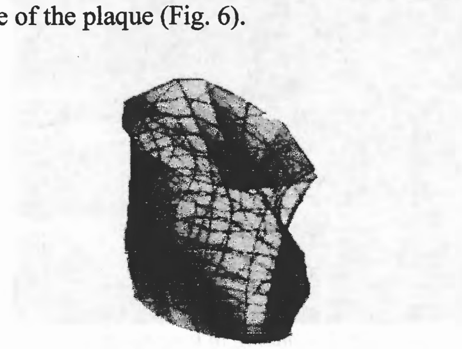

Figure 6: 3-D model of the plaque based on post-operative specimen

The next step is the reconstruction of the geometry of the plaque based on the preoperative DUS images of the respective patient, the reconstruction of the geometry of the artery around the plaque and then the estimation of the stenosis.

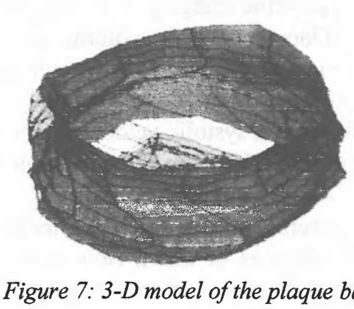

Figure 7: 3-D model of the plaque based on pre-operative DUS images

DUS images depicting both transverse and longitudinal views of the carotide and the plaque have been used for this purpose. The images were scanned and the outlines of the plaque and the artery were digitized from the computer images of the digital images. Again, computer 3-D modeling techniques were used to reconstruct the 3-D model geometry both in wireframe and in rendered format. The functionality of this 3-D modeling program gives the user the option to manipulate the model in 3-D space and to measure and calculate distances, areas and volumes on the computer screen. Therefore it is possible to directly obtain the stenosis from the model of the ICA and the plaque (Fig. 7).

4. RESULTS

The degree of stenosis was calculated from both models and these independent calculations derived very similar results. More specifically the stenosis calculated from the model based on the DUS images was found to be 65.2%, while the stenosis calculated from the model based on the real plaque specimen was found 64.3%, that is a difference of 0.9 percentage units.

The preliminary results indicate that DUS images can lead to modeling, calculations and measurements with excellent data accuracy. Quite as important are the by-products of the 3-D modeling process. The developed stereo models give, for the first time, the possibility to accurately estimate the surface and the volume of the atheromatic plaque and its components. This leads to the ability to measure the blood velocity and pressure inside the plaque (with simple application of the Bernoulli law).

The next step to be pursued is the extraction of qualitative or "thematic" information regarding the plaque substance, from the DUS images. In this step the findings during the pathological examination phase serve as "ground truth" and the digital microscopic images will be processed through automatic classification and "computer training" algorithms. The aim is to investigate the ability to automatically obtain this information from DUS images.

5. CONLUSIONS

From the above description of materials and methods used, as well as from the results illustrated the following conclusions are reached:

- The expertise, materials, methods and techniques available indicate that this approach is clearly feasible.
- The technology necessary for carrying out the work exists. Some further developments are required in order to refine technical issues.
- The proposed method is capable of producing a system for modeling, measuring and providing information valuable for diagnosis and treatment for carotid artery disease.
- The approach give, for the first time, the possibility of accurately measuring other (than degree of stenosis) as important factors, providing thus a more powerful diagnostic tool.
- The approach has the potentiality to become standardized and subjective, limiting the degree of human error or expertise.
- It has also built-in capabilities of becoming fully automatic and real-time.

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