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Applications of Picture Processing, Image Analysis and Computer Graphics Techniques to Cranial CT Scans

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Systems for the processing and representation of cranial computed tomograms have become a significant addition to the use of computers in medicine, particularly radiology. This paper tries to outline a global view on some of the important technical capabilities such systems can provide using techniques from Picture Processing, Image Analysis and Computer Graphics. Experimental results of the COMPACT Project are presented wherever appropriate. Further thought is also given to the framework in which CT processing may take place. To ensure clinical efficacy a concept of a Medical Work Station as part of a distributed computing network is discussed. Some consideration is then given to the physicians possible working modes within such a system.

INTRODUCTION

In the process of medical diagnosis and therapy, information is usually presented by means of the written word, pictures, graphics and the spoken word. For a particular patient the sum-total of this information may be labelled the medical record (MR). In the interest of a patient oriented health care system there are a number of important if not vital requirements on how the information in the MR should be organized and used, e.g. there should be

a) access to the information in the MR at the right place in the right time by the right people,
b) maximum utilisation of information for diagnostic and therapeutic purposes,
c) reliable linkage of all patient specific information into one MR.

In addition, there are some desirable features of data representation and processing for the medical practioner, e.g. there should be

d) uniform, structured and easy to understand data representations of MR's,
e) easily extendable MR's,
f) safe, protected and easily accessable MR's,
g) speedy statistical data gathering facilities on MR's,

and most important of all

h) flexible conferencing and consulting mode facilities using MR's and all modes of communication (i.e. word, picture and voice communication).

It is suggested in this paper that each of the above requirements for information management and evaluation can be maximally satisfied by using medical work stations (MWS's) in a distributed computing network.

The development of such a system is currently being carried out at the Institut für Technische Informatik at the Technische Universität Berlin. The principal application of the MWS's is for the management of neurological disorders and includes a system for the Computerized Management, Processing and Analysis of Computed Tomograms (COMPACT).

Processing and analysis of Computed Tomograms (CT's) are mainly in support of require-

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ment b). They are seen in the framework of picture processing and image analysis and are discussed respectively in chapter 2 and 3 [Sections on Picture Processing Techniques and Image Analysis Techniques].

Computerized management of CT's covers a wide spectrum of activities in support of all of the above mentioned requirements and features for MR processing. Computer Graphics is particularly suitable for feature d) and will be discussed in chapter 4 [Section on Computer Graphics].

Our approach to provide for feature h) will be outlined in chapter 5, that is transmission of CT's in a network for communication and filing purposes.

PICTURE PROCESSING TECHNIQUES

Digital picture processing techniques, generally aimed at a transformation from one picture to a modified and improved picture have to meet when applied to computed tomography the following demands:[1]

a) improve the picture with respect to the human perceptional ability and/or
b) reduce noise and scan and motion artifacts and/or
c) obtain a more suitable representation of the picture for the segmentation process.

To achieve the most suitable representation of the computed tomograms for the physician the main requirement for improving the visualization of the anatomic and pathologic picture content. This may require noise smoothing, edge and contrast enhancement and pseudo colour transformations. When automated analysis by an off- or on-line computer system is intended demand c) may be further divided into the categories i) improvement of the picture characteristics, e.g. edges and contrasts, and ii) data reduction to limit the size of the picture matrix.

Computed Tomogram Characteristics

In general, the two-dimensional representation of a picture contains a degradation which is dependent on the picture formation process. Degradations may be modeled by a convolution function over the picture and an additive component, the noise. For X-ray imaging in computed tomography, there may be several sources of degradations, e.g. as part of the modulation transfer function of the scanner, caused by scattering photons during traversal of the object and the nonlinearity of energy source and detectors, and the influence on picture quality of the algorithms for reconstruction from projections. Furthermore, picture quality is dependent on several parameters, in particular the scan energy, the number of projections and the spatial resolution.

It is obvious that all parameters are highly scanner dependent. Current work embedded in the COMPACT Project focus on cranial computed tomograms obtained from the EMI CT1010 scanner at the Department of Computed Tomography of The Free University Berlin. The computed tomograms are defined as a digital two-dimensional array with a total of 160×160 picture elements (pixels) each of which is associated with a numerical integer value in the range $-1000 \ldots 1000$ (HU-value) which corresponds to the average density of brain structures in a volume element (voxel) sized $1,5 \times 1,5 \times 10$ mm^3. Notwithstanding the two-dimensional representation of the computed tomogram, the real information per pixel is of a three-dimensional nature.

Data Reduction

The task of data reduction may be defined as the suppression of irrelevant information within the entire picture domain. In cranial computed tomograms, the relevant structural content for diagnostic and therapeutic purpose is the distribution of HU-values describing the attenuation coefficients of the brain tissue. For computer processing purposes it is useful to reduce the great number of bits per tomogram so as to achieve only storage of the matrix line segments which refer to brain.

The preprocessing module for cranial computed tomograms includes smoothing, skull detection, detection of brain line segments and the computation of several statistics on the brain pixels. Cranial computed tomograms are stored on magnetic tapes by the processor of the EMI CT1010 scanner and read by an ITEL AS-5 of the Department of Computer Science at the

Technical University Berlin. The complete set of picture matrices is transferred onto the disks of the graphics system Adage AGT 130 via a 4800 baud data line. The preprocessing algorithms were designed for scan-mode processing via a software buffer holding 5 tomogram lines at a time. Subsequent processing has been adapted to the line-oriented tomogram storage structure on the tape and the limited main core size of 32K words of the ADAGE system which does not allow core resident storage of the complete tomogram matrix during processing.

Skull detection is performed simply by fixed thresholding of the smoothed pixels in the line buffer. Fixed thresholding is enabled by the fact that bone appears in a constant range of HU-values on the tomograms. After Skull detection each row lying within the skull is checked for brain candidates by a decision on the HU-value statistics of the pixels per line. By this simple and also fast method a distinction between brain and background is made. Once a brain line segment is detected several statistical computations are made on the line buffer:

mean HU-value and standard deviation of the HU-values of the brain,
the first order histogram of brain pixels,
the brain area,
the center of the entire brain region on the tomogram by moment analysis, and
the symmetry line, which may be rotated due to patient position in the gantry by the principal axis method (details are given in[2]).

After preprocessing the reduced tomogram data are stored in a core resident list and can be referenced by a line descriptor block containing line and column indices followed by the pixels HU-values.

Preprocessing was tested on the whole CT data base including 120 cranial computed tomograms. The results for skull detection and background suppression were very exact. Preprocessing is done in approximately 60 seconds execution time including disk accesses and data transfer from disk to main core.

Image Enhancement

Noise degradation inherent in the tomogram is smoothed by a conventional average operator defined over a 3×3 neighbourhood. Since the averaging operator is in no sense adapted to the specific origin of the noise, edges are blurred within the brain pixels and image quality is overall degraded.[3] Designing noise adapted smoothing operators needs careful analysis of the theoretical background of noise origin and properties in CT scanners.[4]

However, not only smoothing techniques are important to improve CT images but also techniques for enhancement of CT images.[5] These can either sharpen edges or make low contrast differences visible to the physician. Such a procedure may give substantial help to the physician in the diagnosis of low contrast mass lesions for which the border to surrounding tissue may not be clearly visible. Furthermore, the interior of low contrast lesions can be more clearly analyzed after contrast or edge enhancement.

In addition, pseudo colour transformations can improve visibility of neuroanatomic and -pathologic structures. The selection of a gray-value to pseudo-colour mapping scheme must take into account that the range of colours does not overtax the perceptional ability of the physician.

The solutions to some of the sketched problems are part of the continuous development of the COMPACT system.

IMAGE ANALYSIS TECHNIQUES

In general, two distinct approaches to computerized analysis of the structural content of computed tomograms have been established:

the interactive and
the automated CT image analysis approach.

To achieve an optimal synergesis in an interactive environment between the physician and computer system careful design of the man-machine communication module is important. Numerous papers on interactive analysis of computed tomograms have been published within the last few years. An introduction to the above mentioned problems is given in,[6] a survey can be found in.[7]

Common to interactive and automated CT image analysis was the emphasis given to the diagnostic evaluation of the brain ventricles.

Linear distance measures derived from pneumoencephalography were adapted to CT for descriptive analysis of atrophic diseases and infant hydrocephalus. To overcome their two-dimensional nature and also facing the three-dimensional nature of CT information,attempts have been made to estimate the ventricular volume on computed tomograms.

The development of techniques for automated analysis of CT images with respect to the brain ventricles are based on three demands:

a) to overcome the tedious work of ventricle outlining over a range of up to 12 tomogram slices,
b) to yield an exact parameterized description of the three-dimensional morphology of the ventricles, and
c) to facilitate a realistic visualization of the complex ventricular structure.

It is easily seen that

a) implies automated image segmentation and object recognition,
b) means the automated determination of the ventricular volume, and
c) requires a three-dimensional display with shading, hidden surfacing, and various picture transformations well known in Computer Graphics.

Segmentation

The selection of an appropriate segmentation scheme for cranial CT scans was influenced by the following design demands:

a minimum on computational cost and storage requirements during processing time,
a fast and therefore quite "simple" approach,

and

optimal adaptation to the line-oriented computed tomogram storage structure.

A dynamic thresholding approach was chosen (contrary) to the approach with fixed threshold in[8]) and implemented in FORTRAN IV on the ADAGE AGT 130 graphic system.

The cerebrospinal fluid-filled cavities like ventricles, cisterns and the subarachnoid space are defined on the cranial computed tomogram by a characteristic range of HU-values and are well contrasted to the surrounding HU-values of brain tissue. The latter feature enables thresholding of the tomogram picture matrix with an automatically selected dynamic threshold range (it has been found that due to slice-, patient- and scan-energy-dependent CSF range variations, fixed thresholding yields unsatisfactory results).

Some considerations have also to be given to the CT generation process. The HU-values of the pixels in the two-dimensional tomogram matrix result from averaging the attenuation coefficients of the three dimensional density distribution of sometimes more than one material within one voxel sized $1{,}5 \times 1{,}5 \times 10\ \mathrm{mm}^3$. So, voxels defining the brain/ventricle edge may contain brain tissue as well as CSF and are therefore given a higher HU-value than the purely CSF containing voxels (usually referred to as "partial volume phenomena", the amount of, for example, CSF within one voxel is called "partial volume ratio" pvr). The upper CSF range bound is therefore defined by the maximal HU-value of the pixels representing the ventricular system.

For analysis of the ventricle/brain edges a sum-type gradient is computed over the entire brain on the tomogram and its magnitude is correlated with the HU-value at corresponding pixel indices by a modified two-dimensional (joint) histogram following the notion in.[9] A projection over all maximal gradients yields a one-dimensional histogram of HU-values of possible edge pixels.[7]

One problem, however, has to be discussed in more detail. In the ideal case, the resulting one-dimensional histogram is unimodal and its maximum gives the HU-value of the most frequently occuring pixels at the ventricle/brain edge associated with maximal gradients. However, the ventricle/brain edge has, in general, a non-constant edge profile due to a varying partial-volume ratio along the edge (analysis of brain anatomy makes it clear that the voxels at the periphery of the frontal horns must contain less CSF than those at the periphery of the third ventricle). In general, the histogram is bimodal referring to an edge part associated with minimum and one associated with maximum partial volume ratio. In cases where two strong peaks

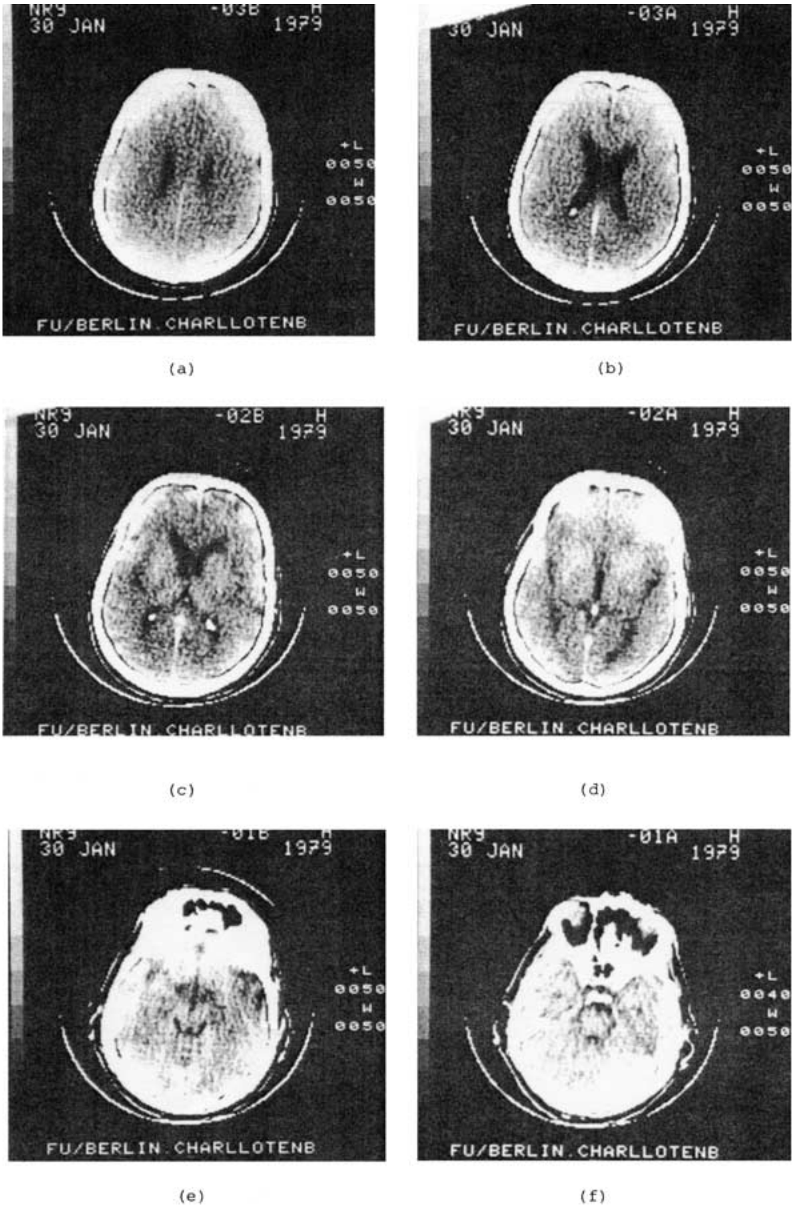


Fig 1a-1f. Computed tomograms of one from 10 skulls (specially prepared for this experiment from dissections).

are present the valley of the histogram is chosen as threshold. It is clear that such a pure global analysis for threshold determination results in only an estimation for the upper threshold bound hence the influence of local contrast is ignored. This means that in respect to the distribution of partial volume ratios within the slice only the ventricular system or the external liquor spaces are segmented well. If the external CSF containing regions are segmented exactly, the ventricles may well be in general too large and vice versa. An improved version of the segmentation scheme will combine both global statistics on the edges present within the tomogram and local contrast properties on a defined pixel neighbourhood.

The lower CSF range bound is chosen from the first non-zero entry of the overall brain histogram with minimum HU-value. Results of the segmentation scheme applied to computed tomograms in Figs. 1a-1f, are given in Figs. 2a-2f.

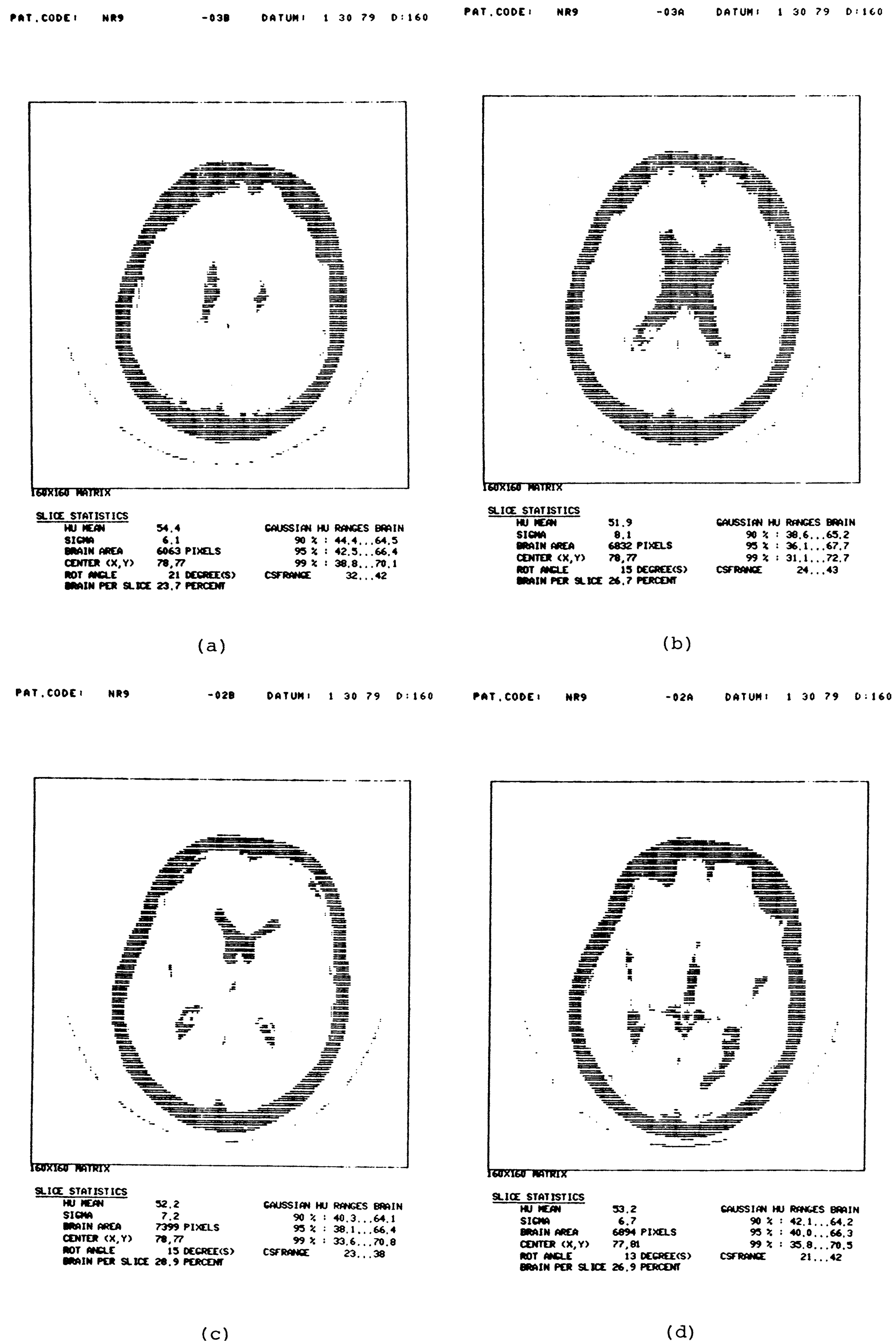
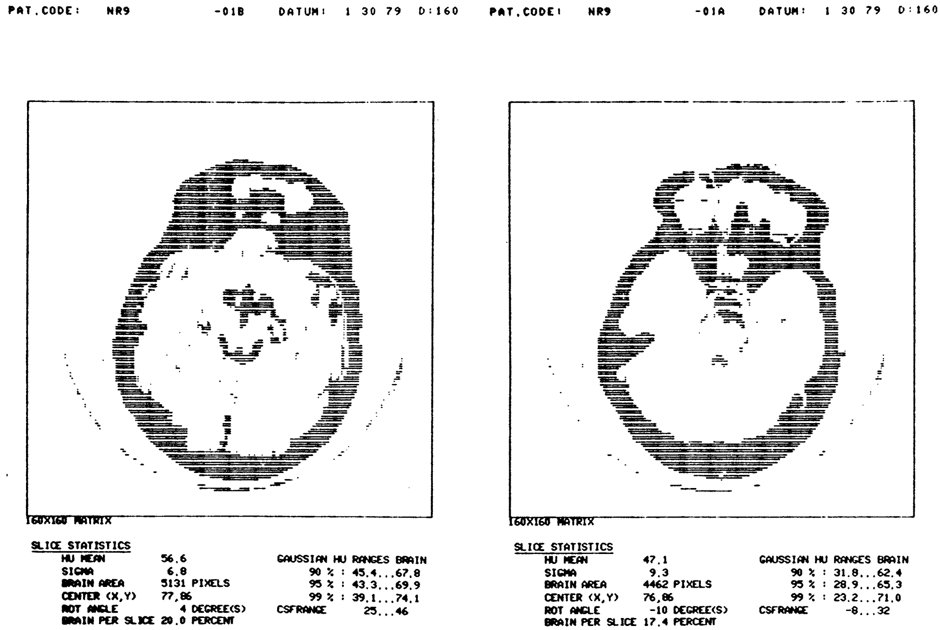


Fig 2a-2f. Results of the segementation applied to the computed tomograms in Figs. 1a-1f.

After automated threshold selection, a line sequential thresholding operation is performed on the core-resident brain line segments yielding CSF region line segments. The line segments are grouped together into regions via overlap checking between two abutting line segments in



(e) (f)

Fig 2. Continued.

two consecutive lines (a method similar to[10]). The region growing approach was designed to save subregions which originate by merging and splitting occurrences on a line and to generate a hierarchic list-oriented picture.

Picture description is performed

during region growing to compute area, mean etc.

and

after region growing on the generated data structure.

The basis for picture description is an assumed computed tomogram geometry defined by the brain center and the (possibly rotated) symmetry line. The brain is divided into four quadrants allowing for positional and relational orientation of the CSF regions within the entire brain on the computed tomogram. Each region is labeled and described by a set of descriptors: area, circumscribing rectangle, mean of HU-values, region center coordinates, distance to brain center, angle with symmetry line, index of quadrant and a ventricle candidate indicator with value either 1 or 0. The latter descriptor excludes all regions with minimal size and peripheral position from subsequent analysis as described in the next section (in Fig. 3 results from picture description of the segmented computed tomogram in Fig. 2d are shown).

The segmentation of CSF-filled brain cavities on cranial CT scans was tested on the CT picture data base of 120 computed tomograms with patients aged 20-75 years. A subset of 61 computed tomograms (tomograms with only third or fourth ventricle were not taken into account) with normal and diminished as well as dilated ventricles was processed and presented to three physicians with clinical experience in CT scan analysis. They were asked to rate the resemblance between the ventricles on the tomographic Polaroid photographs and those on the hardcopies of the computer processed tomograms. Given a range from 1 to 6 (1: good resemblance, 6: bad resemblance) the overall judgement for segmentation of the ventricles was: 1 (6%), 2 (35%) , 3 (31%), 4 (21%), 5 (7%) and 6 (0%).

It is interesting to note that the judgements for range 4 to 6 are due to the binary representation of the segmentation results on the hardcopies. The physicians therefore felt that the ventricles were in general to large. Comparison by eye between hardcopy and tomographic Polaroid photographs requires the subjective extraction of the ventricle/brain edge from the photograph. This edge shows a strongly reduced gray-value range while the ventricle/brain edge on the hardcopy is defined by analysis of the original HU-value range. If the segmented region is too large within an accepted error range, the influence of the peripheral pixels (belonging to brain tissue but "classified" as CSF) on the volume determination is rather small (partial volume ratios of less than 6%)and can therefore be ignored. Furthermore, the judgements of the physicians differ significantly, e.g. physician C: 4 (5%), 5 (1%), physician A: 4 (35%) , 5 (15%). One fact was also clearly observed: the better the picture quality, the better the segmentation results.

The tomogram segmentation needs less than 15 seconds CPU time including automated selection of threshold range, thresholding, region growing, data structure generation and picture description.

Recognition of the Ventricles

The task of automated recognition of the brain ventricle parts on contiguous computed tomograms was realized by a model-guided recognition strategy utilizing contextual information. Two types of context are available:

- the inter-region context per slice, given by the picture description and
- the inter-slice context, given by assumptions on the probable occurrence of specific parts of the ventricular system on the next processed computed tomogram, dependent on already recognized ventricle parts.

The inter-region context is revealed from the picture geometry and defines the positional relation between ventricle parts within one slice. Estimates of the positional range in which a ventricle part may be expected on a computed tomogram are obtained with the aid of anatomic a priori knowledge. The a priori knowledge for each ventricle part is represented by a production system with several highly problem- and object-dependent production rules.

The definition of inter-slice context is a much more complex problem and should aid the recognition, strategy "to-look-where-for-what." Each tomogram is considered a frame within the complete tomogram sequence. The sequence is processed top-down starting with the tomogram with first occurring ventricle part. The structural top-down hierarchy of the ventricular system in man, namely from the "top" cella media "down" to the fourth ventricle, renders possible a forecast on the probable occurrence of ventricle parts on the next tomogram within the sequence and may be described by a tree (each vertex in the following simplified tree may be present n times on n contiguous tomograms).

```
                cella media
              /             \
  frontal horns         occipital horns
        |                      |
  third ventricle        trigonum
        |                      |
  fourth ventricle       inferior horns
```

Once the initial cella media regions are recognized, a context mask is defined by the circumscribing rectangle to minimize the search range for structural continuation on the tomogram to be processed next. All regions (objects) within the context mask range are treated as possible ventricle candidates and a decision has to be made on the selection of the abutting ventricle parts on contiguous tomograms.

The decision function may be executed on various criteria such as shape, size, location within the context mask, maximal overlap between context mask and region area, nearest neighbourhood of region centers or more general, on the best match with the ventricle model parameters. The main problem in providing sufficient inter-slice context is the high variability of the structure of the ventricular parts. Some parts may either be connected or isolated, shifted, dilated, diminished or even be absent due to the presence of a certain pathologic disorder, patient specific anatomical alterations, the position of the head in the scanner gantry (causing non-standard slices in respect to the orbito-meatal line as basis proposed for CT head scanning), the imperfect scanner resolution and the presence of specific noise and

IMAGE ANALYSIS

11 REGIONS (TYPE : UNCLASSIFIED CSF) FOUND [7 REGIONS TYPE: VENTRICLE CANDIDATE]

LABEL	AREA	CIRCUMRECT	HU-MEAN	XC	YC	DIST	ANGLE	QUADR	CAND
1	2	81 82 24 24	35	81	24	53	3	1	0
2	267	70 98 47 69	31	81	58	19	8	1	1
4	2	120120 56 57	38	120	56	46	63	1	0
8	9	51 52 70 75	37	51	72	27	79	2	1
9	9	77 79 77 81	36	78	79	2	0	3	1
10	74	54 65 87101	33	58	93	25	51	3	1
11	5	120120 87 91	31	120	89	43	74	4	0
15	6	88 91 92 94	37	89	92	18	36	4	1
16	7	94 96 94 97	35	95	95	24	43	4	1
17	1	34 34 97 97	37	34	97	48	65	3	0

Fig 3. Results from picture description of the segmented computed tomogram slice 2B (Fig. 2d).

artifacts. The recognition strategy has to be invariant against these variabilities.

For achieving maximal flexibility, the recognition strategy must show independence from the number of processed tomographic slices. If the decision function fails, the recognition strategy will initialize the search for the next ventricle part on the current tomogram by a top-down traversal of the tree. If a part of the ventricular system, expected to be the next in the structural hierarchy, is not present, an unusual change in structural content is detected.

The overall recognition module is supervised and directed by a control structure.

The model-guided recognition of the ventricles results either in the description of the structural content of the complete tomogram sequence (see Fig. 4) allowing for further diagnostic evaluations or in the abortion of the processing if some conspicuous differences are present on the current tomogram (details of the proposed methods will be given in[7]).

Ventricle recognition was tested on the whole CT data base, 16 tomogram sequences were analysed. For 10 sequences, the detection of the ventricular parts (except the occipital horns, for which the algorithms are currently under implementation) was correct. From the remaining sequences, 3 were analysed incorrectly due to insufficient inter-slice context definition for the basal tomograms and for 3 sequences recognition was aborted due to significant structural changes. For ventricle recognition less than 3 seconds CPU time is spent.

Analysis of the Ventricles

The goal of the current program version is to achieve an exact estimation of the volume of the human brain ventricles. The partial volume phenomena does not allow simple multiplication of the overall ventricular area by the pixel size and slice thickness but needs a further processing step to retrieve the information of the three-dimensional brain tissue/CSF-distribution within the slice out of the two-dimensional computed tomogram picture matrix. The first attempt on automated partial volume corrected determination of the volume of fluid-filled) brain cavities was made in[11] where a formula was given to compute the partial volume ratio of CSF within one voxel (however, the volume of all CSF-filled brain cavities was computed, not the ventricular volume). The summation of all partial volume ratios of the ventricle parts multiplied by the actual pixel size and slice thickness yields the most correct volume estimation of the ventricular system.

$$\mathrm{pvr} = \frac{\text{HU-value} - Z^{\mathrm{csf}}}{Z^{\mathrm{brain}} - Z^{\mathrm{csf}}} 100\% \qquad (11)$$

The main problem in this procedure is the correct estimation of the typical HU-values for brain, Z^{brain}, and cerebrospinal fluid, Z^{csf}. The result of volume determination for the recognized ventricles in Fig. 2a is given in Fig. 5.

The recognition of the ventricle parts per slice and per sequence allows for further analysis of the ventricular system. The characteristic descriptors of the ventricular system, e.g. occurrence/non-occurrence, symmetry, shape and position, are important indicators for the presence of some pathologic disorders on the slice and may give helpful information to the physician for diagnosis and therapy. Results from the ventricle recognition like statements on absence, size, positional shifting and structural

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VENTRICLE RECOGNITION PROTOCOL
******************************

SLICE:  NR9          03B

        ! LEFT CELLA MEDIA  DETECTED (LABEL:  1)
        ! RIGHT CELLA MEDIA DETECTED (LABEL:  2)
        * SLICE CONTEXT: ISOLATED CELLA MEDIA

SLICE:  NR9          03A

        ! CELLA MEDIA DETECTED  (LABEL:  2)
        * SLICE CONTEXT: CONNECTED CELLA MEDIA

SLICE:  NR9          02B

        ? NO CM CONTINUATION
        ! FRONTAL HORNS DETECTED  (LABEL:  2)
        * SLICE CONTEXT: ISOLATED FRONTAL HORNS/3RD VENTRICLE
        ! THIRD VENTRICLE DETECTED  (LABEL:)
                                              9
        # OK RECOGNITION

SLICE:  NR9          02A

        ! FRONTAL HORNS DETECTED  (LABEL:  4)
        * SLICE CONTEXT: ISOLATED FRONTAL HORNS/3RD VENTRICLE
        ! THIRD VENTRICLE DETECTED  (LABEL:)
                                              6
        # OK RECOGNITION

SLICE:  NR9          01B

        ? NO FRONTAL HORNS CONTINUATION
        ? THIRD VENTRICLE NOT IN EXPECTED RANGE
        ? NO THIRD VENTRICLE CONTINUATION
        ? FOURTH VENTRICLE MISSING
        # OK RECOGNITION

SLICE:  NR9          01A

        ! FOURTH VENTRICLE DETECTED  (LABEL: 35)
        # OK RECOGNITION

RECOGNITION DONE
****************
```

Fig 4. Structural content of the CCT sequence derived from ventricle recognition model.

asymmetry of the ventricle parts may serve as a priori knowledge to be input to an image analysis procedure for detection of pathologic processes. Such a procedure will be included in a future version of the COMPACT software system and will comunicate with a data base describing pathologic processes in detail. Furthermore, global and local parameters on the hemispheric HU-value distribution can be computed (like textural features) for determining hemispheric asymmetries to aid in the search for probable pathologic processes.

Verification of the ventricular volume determination requires much effort and work in this direction is still in progress. The heads of 10 bodies were scanned (by Dr. med. S. Lange, formerly Department of computed Tomography, Klinikum Charlottenburg, Free University of Berlin), the brains were then removed from the skull and sliced into 2 mm layers. A planametric evaluation of the ventricles per layer yields a fairly exact estimate of the volume which has to be corrected because of some changes in the brain tissue (density, volume)

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VENTRICLE VOLUME ANALYSIS
*************************
ZBRAIN: 44 ZCSF: 26

SLICE:      03B
REGION LABEL: 1      VOLUME:   0.97 ML
REGION LABEL: 2      VOLUME:   0.18 ML

SLICE:      03A
REGION LABEL: 2      VOLUME:   9.88 ML

SLICE:      02B
REGION LABEL: 2      VOLUME:   4.12 ML
REGION LABEL: 9      VOLUME:   0.08 ML

SLICE:      02A
REGION LABEL: 4      VOLUME:   0.02 ML
REGION LABEL: 6      VOLUME:   1.01 ML

SLICE:      01B

SLICE:      01A
REGION LABEL:35      VOLUME:   0.39 ML
OVERALL VENTRICULAR VOLUME:  16.65 ML
```

Fig 5. Volume determination of the recognized ventricle system.

due to death, freezing-in the whole body and fixation before slicing. Subsequently, the correlation between the volume computed by automated analysis of the tomograms to the volume evaluated by manual planametry can be determined (for details see[7]).

The time required for volume determination of the ventricular system depends on the number and the size of the ventricle parts per slice and is for one sequence with 6 tomograms less than 12 sconds CPU time.

COMPUTER GRAPHICS

Computer Graphics (CG) has established itself as a powerful tool for three-dimensional reconstruction and display of CT scans. Although 3-D reconstruction is not a traditional CG technique it can make extensive use of graphic oriented data structures and is therefore discussed conveniently as part of CG. 3-D display techniques, however, have a long tradition in CG and many of these techniques may therefore be applied to CT problems.

Perhaps the first system with CG capabilities was demonstrated by Maziotta and Huang in 1976.[12] Contourlines in a CT-slice are defined manually using a light spot controlled by a joystick. Invisible parts of this contourline (when observed from a given viewpoint) are then masked out and followed by a definition of polygons between adjacent contourlines. This type of masking makes an expensive hidden surface algorithm unnecessary. Manual input of contourlines and the inability of the system to display concave objects (caused by restriction of one contourline per CT-slice) are, however, a definite disadvantage.

Semiautomatic extraction of contourlines in CT's employing manual error correction has been implemented by Sungenoff and Greenberg in 1978.[13] B-spline and Cardinal-spline techniques are used for smooth surface reconstruction. The quality of the picture appears to be excellent and is made even more attractive through transparent display of the skull. Not so advantageous is the strong dependence on interpolation between adjacent contourlines. The contourlines of the 5 CT-slices used, for example, for the reconstruction of the ventricular system may therefore well suppress important anatomical detail.

A system not based on "stacking" was introduced by Herman and Liu in 1977.[14, 15] Surfaces of three-dimensional objects are directly represented in a three-dimensional matrix by the exterior faces of the boundary voxels. Because voxel faces are of equal size and are normal to the axes of a three-dimensional Euclidean coordinate system, the hidden surface and stacking algorithms can be kept simple and fast.[16]

All methods so far considered, however, do not take account of the shape of objects within the 8-13 mm thickness of the CT-slice.

3-D Reconstruction

In the COMPACT system three-dimensional reconstruction of objects is also carried out within the CT-slice.[17] Input to the reconstruction process consists of the pvr-values and a suitable hierarchical data structure. Both are supplied by the ventricular recognition module. Reconstruction is then based on the following three steps:

1. Search for object regions which show contiguity between adjacent CT-slices.
2. Determination of the probable spatial orientation of the pvr-part within a slice.
3. Definition of the contourlines of the object in n subslices for each CT-slice.

The first process is based on the assumption, that if two voxels of the same object but from adjacent slices share a common face, their content form a continuous column of tissue or CSF.

In the second step the pvr-value dependent alignment takes place, that is a shifting of the respective tissue or CSF to the superior or inferior boundary of the slice or centering it on the middle of the slice. Although satisfactory results are obtained using this method for alignment, usage of a priori information from anatomic models of the brain is currently being considered.

Finally, each CT-slice is partitioned into n subslices allowing the corresponding contour lines of the object to be defined (similar to the conventional "stacking" approach). Dependent on the size and orientation of the pvr-values some subvoxels of a voxel are positioned inside, others are outside of the object to be reconstructed. The centre points of the subvoxel faces belonging to the surface of the object serve as points for the object contour line (Figs. 6a-6h).

3-D Display

Basically, there are two types of display representations for 3-D objects, they are:

1. wire framed drawings,
2. shaded pictures.

To aid the human visual system in depth perception these display representations can be combined with one or several depth cues, e.g.

1) visibility (hidden line/surface removal)
2) intensity cues
3) perspective
4) stereoscopic views
5) kinetic depth effect (rotation, motion)
6) shadowing
7) transparency

Not all techniques for depth perception are, however, of use for 3-D display of objects reconstructed from CT-scans. For example, perspective and shadowing techniques are of little assistance in the representation of anatomical structures. Other methods, e.g. kinetic depth effects or stereoscopic views, require special technical backup and may therefore not always be easily implemented.

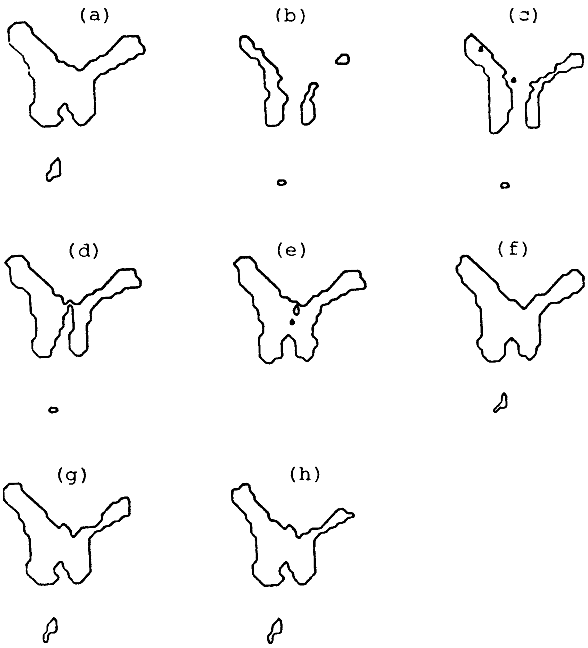

Fig 6. (a) Max. contourline of slice 2B (b-h). Contourlines of seven reconstructed subslices.

The algorithms for 3-D display implemented in the COMPACT project are wire frame plus hidden line removal and wire frame plus kinetic depth effect through real-time rotation. Both display facilities are implemented on a vector display (Fig. 7). Further algorithms for the generation of shaded pictures on a raster display (GENISCO) are in the process of being implemented. One algorithm is based on the method of polygonal definition between adjacent contour lines followed by hidden surface removal and shading. Mapping and branching problems, however, may arise between adjacent contour lines and may defy a solution by automatic methods. A promising approach to this problem, although restricted to a certain class of contour lines, is the algorithm suggested by Christiansen and Sederberg.[18] This algorithm and the method which has been described by Herman and Liu are being investigated in the COMPACT project.

A NETWORK OF MEDICAL WORK STATIONS

The following is a brief summary of the processing facilities which a distributed MWS system should provide. It is assumed that all internal information in the system is represented in digital form.

Medical Work Station (MWS)

As shown in Fig. 8 the main software components of a MWS are:

a) Word processing
e.g. input and editing of constrained and free format text, searching, scrolling, and panning of text for patient history taking
b) Signal and image processing
e.g. preprocessing, segmentation and pattern recognition of one- and two-dimensional data of ancillary investigations

Fig 7. 3-D reconstruction of the recognized ventricle system.

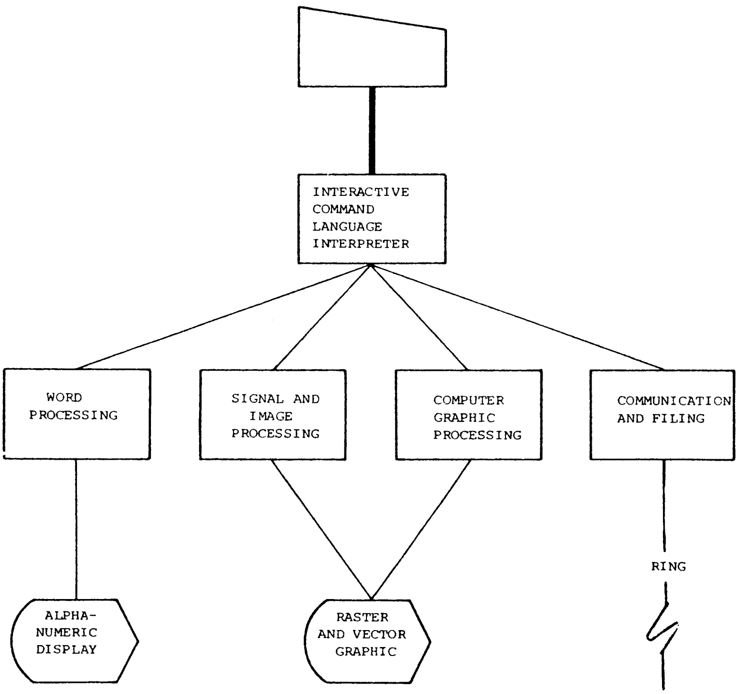

Fig 8. Software components of the MWS.

c) Graphics
e.g. graphic display of one-dimensional signals, two-dimensional images and reconstructed three-dimensional objects
d) Communications
e.g. transmission of voice, text, picture and graphic data, filing of (voice), text, picture and graphic data, hardcopy, command language interpretation

For the system being developed at the Institut für Technische Informatik, facilities at the MWS are at first limited to the processing and representation of electro-encephalograms (EEG), magneto-encephalograms (MEG), and of computed tomograms.

Network

A ring communication facility of the type shown in Fig. 9 is very attractive for interconnecting MWS on a restricted site allowing high bandwidth with very simple control. Communication of a MWS to resources outside the local ring network may be achieved through microprocessor controlled bridges or gateways to other rings or global network facilities. These possibilities, however, shall not be considered further in this paper, the interested reader is referred to.[19,20,21]

Ring

a) Local network facilities
e.g. graduated (incremental) work stations with resource sharing, process to process communication, concurrent transceiv-

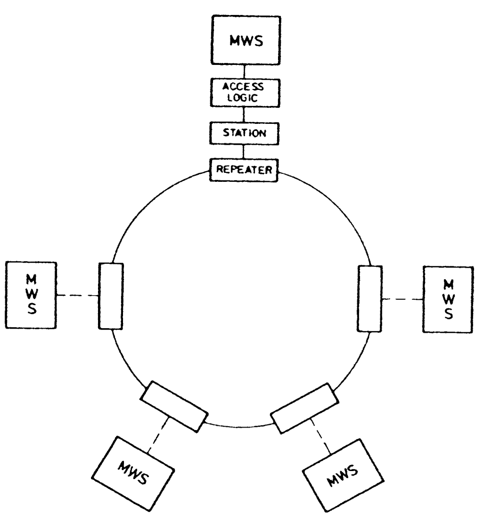

Fig 9. Ring communication for MWS.

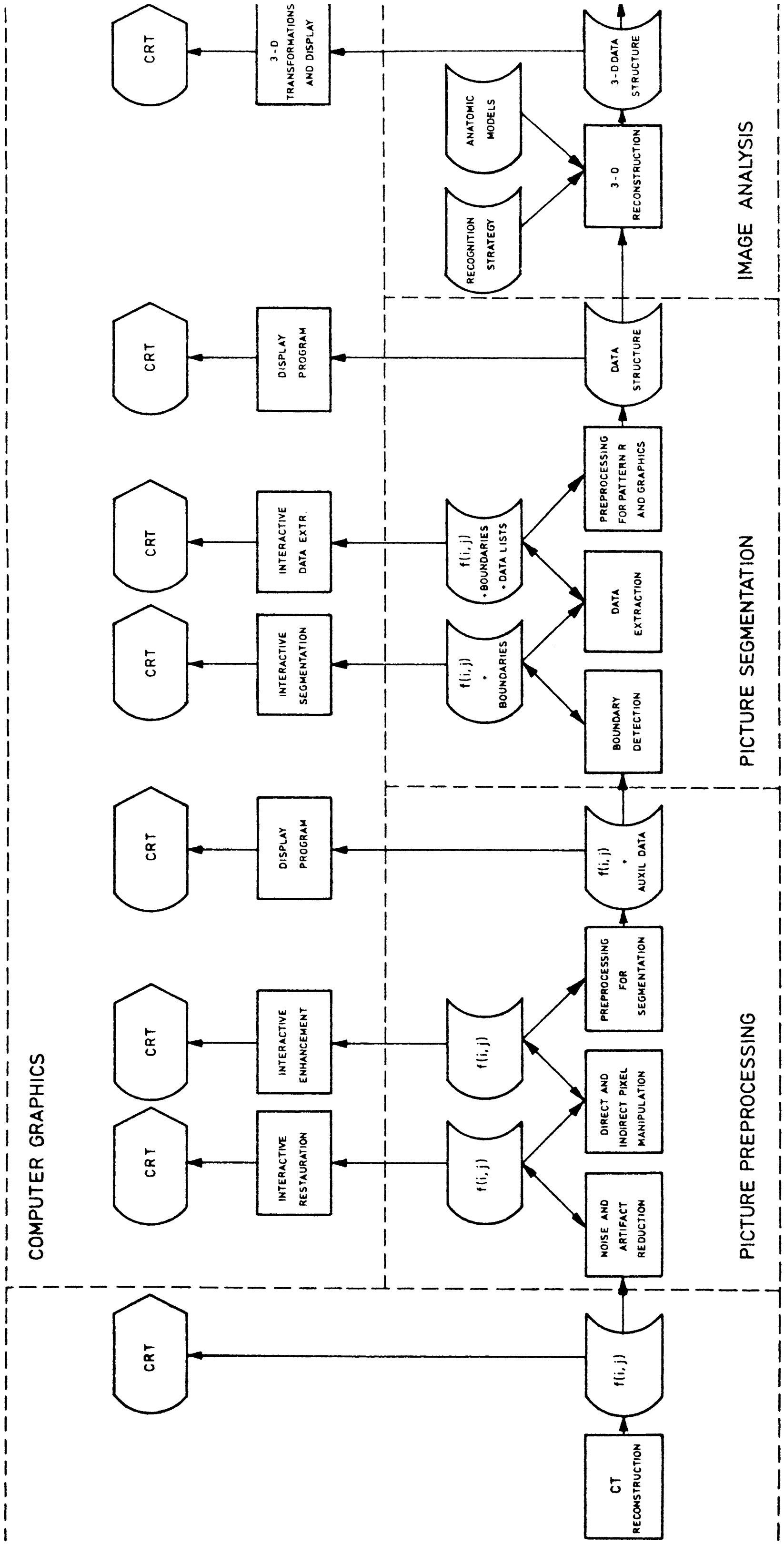

Fig 10. Data flow for the processing of computed tomograms.

ing, information security, conferencing mode

b) Global network facilities
e.g. bridge and gateway controls

Central to this set of facilities is the interactive command language interpreter which controls the user interface with the system as shown in Fig. 8. Its main design features are:

1. Common syntax of driving commands for word, signal, image, graphics, and communication processing
2. Syntax and semantics as much as possible in line with "medical thinking"
3. Menu implementation
4. User oriented software (e.g. "sympathetic software")

Fig. 10 shows the data flow for the processing of computed tomograms between the main software modules of an idealized MWS. Not all facilities may be offered at every MWS, however, the command language interpreter for driving modules will always be present.

CONCLUSION AND AIMS

Although the technical capabilities so far discussed can be used for effectively demonstrating the potential of a MWS system, its real impact on the medical community will depend on its clinical efficacy.

Clinical efficacy addresses itself to the question of assessing the impact of a technique on diagnostic and therapeutic procedures. As regards signal and image processing for computed tomography and following a definition of diagnostic impact given by the Institute of Medicine[22] it is safe to state that the extent to which CT scan information has come to replace other diagnostic procedures including diagnostic imaging, surgical exploration and biopsy, it has proved itself to be efficacious. For many disease patterns it has become the primary diagnostic tool.

Many other sources of information, however, apart from CT scans, must be considered for neurological disorders in the process of differential diagnosis and therapy. That is, information from the patient's history, examinations and other ancillary investigations must be integrated with CT images. A MWS for a particular clinical discipline such as neurology provides a physician with a means to vertically integrate this information into a MR.

In the patient-physician consulting mode a MWS system may promote a shift in the physician's way of working from patient data evaluation towards patient's data gathering and structuring. In the physician-physician conferencing mode emphasis may then be given to patient data evaluation. Clinical efficacy of a MWS system will be achieved when the potential of the two working modes are properly realized.

With this in mind a prototype system is being developed by the COMPACT group of the Technical University of Berlin. Some rather encouraging results in the area of automatic recognition of the ventricular system and other CSF containing cavities as well as ventricular volume determination and 3-D display have already been obtained.

For networking, initially only two workstations will be linked through a >10 Mbit/sec communication medium organized as a ring network. It is expected that this minimum system will eventually be installed in a clinical environment so as to allow some experience to be gained on the impact of this technique on diagnostic and therapeutic procedures.

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