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MRI alone simulation for conformal radiation therapy of prostate cancer: technical aspects

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Abstract—**The value of MRI in defining target volumes and organs at risk is established. Numerous difficulties appear to stand in the way of using MRI alone in dose planning, with the result that this imaging modality is used in most cases in conjunction with computerized x-ray tomography (CT). The aim of this paper is to appreciate these difficulties: geometrical distortion, chemical shifts, dosimetric accuracy. Geometrical distortion measurements were carried out on two 1.5 T MR scanners and the effect of chemical shift and magnetic susceptibility were evaluated in volunteers. The effect on dosimetric calculations of uncertainty in determining electron densities was evaluated too. Geometrical distortion remained at small values: less than 2 mm and 3 mm for field of view of 20 cm and 45 cm. The chemical shift and magnetic susceptibility values obtained, ranging from 0.3 to 3 mm, were well below the theoretical values. The assignment of relative electron densities to only two structures in MR images seems to permit dose planning that is identical with that obtained with CT. None of the technical obstacles mentioned represents a stumbling block. The access to MRI facility could represent a persisting problem.**

Keywords— **MRI, Conformal radiotherapy**

I. Introduction

External beam radiotherapy is an effective treatment of prostate cancer, as surgery and brachytherapy. Using conformal radiotherapy, target volumes and organs at risk are defined directly on medical images, with the choice of more complex and more conformal dose distributions, which would make it possible to improve local control and to minimize adverse side effects. The type of examination currently used to delineate volumes is Computed Tomography (CT), on account of its geometrical precision and the information that it provides on electron densities. Thanks to its excellent soft tissue contrast, Magnetic Resonance Imaging (MRI) ensures better delineation of the prostate, particularly of the apex and seminal vesicles. MRI is increasingly used, by associating it with CT via co-registration techniques, which are more or less sophisticated and more or less accurate. In this case, MRI is used to define volumes and organs at risk, while CT is used for dose planning and to check the position of the patient during treatment. The accuracy of different algorithm image fusion can easily be evaluated with phantoms, but in routine practice there is no gold standard method to evaluate fusion between two exams.

The use of MRI alone use would eliminate the localization uncertainty introduced by image matching and also make it possible to dispense with an additional imaging examination that is costly and is difficult to coordinate with the MRI examination in daily practice. Additionally the use of MRI alone could save patient, staff and machine time. The obstacles usually mentioned are geometrical distortion and distortion linked with magnetic susceptibility and chemical shift, the lack of electron densities information for dose calculation and digital radiography reconstruction (DRR).

Ideally, an MRI scanner has a magnetic field B_0 that is uniform throughout the whole examination area and gradients that are perfectly linear and orthogonal. In practice, the spatial heterogeneities of B_0, whether intrinsic or due to the object under study, induced eddy currents, and non-linearity of the gradients, produce distortions that increase with distance from the center of the field. They can be measured using phantoms of known geometry.

The magnetic susceptibility of a body indicates the way in which it is magnetized under the effect of a magnetic field, and the intensity with which this occurs. Owing to their non-homogenous susceptibilities, which differ from that of the outside environment (air), the tissues placed in the apparatus locally disturb the main magnetic field B_0. Local geometrical distortions, as well as losses of NMR signal owing to incomplete refocalization of the spins, thus occur, particularly at the extremities and at the air-tissue interfaces. These distortions are usually not considered in conventional imaging because their spatial range is limited and their amplitude is small. However few authors find maximal values from 2 to 5 mm [1-2].

The resonance frequency of hydrogen nuclei varies slightly from one molecule to another on account of their electron environment, which locally modifies the main field B_0. As spatial location is linked with resonance frequency in the frequency encode gradient direction (the FEG direction), the fatty tissues will be shifted in relation to water in this direction (chemical shift) by a value proportional to the main magnetic field B_0 and inversely proportional to the intensity of the gradients. Chemical shift can be perceived more clearly in the area of the abdomen and the pelvis than in other locations (particularly the brain) owing to the larger quantity of fatty tissues and owing to the lower gradients used for the large FOV's required for these acquisitions.

Regarding the lack of electron density information in MRI images, some studies have shown that there is no significant

difference in dose calculation between homogeneous and heterogeneous geometry for the pelvic region [3] whereas others authors state tissues heterogeneities must be taken into account [4-5]. In this work the usefulness of heterogeneity correction was studied; the spatial location of errors and their impact on dose planning were examined too.

II. METHODOLOGY

1 - Geometrical distortion and chemical shift

a) Intrinsic geometrical distortion

Distortion measurements were determined on two standard 1.5 Tesla MR scanners, a Magnetom Vision (Siemens®, Erlangen, Germany) and a Gyroscan Intera (Philips®, Eindhoven, Netherlands). The phantom used, measuring 400 mm x 300 mm x 210 mm, was composed of 730 glass spheres arranged in a 3 cm sided cube pattern immersed in a 1,2-propandiol solution. The phantom was imaged with a body coil with a T2-weighted sequence conventionally used for prostate imaging (Turbo Spin Echo, TR = 9900 ms, TE = 120 ms, 4 mm thick contiguous axial, sagittal and coronal slices, 512x512 matrix, FOV 45 cm). The phantom was first studied with CT to know its exact geometry. The deviation between the theoretical and measured positions of the spheres gave distortion as a function of distance to the center of the field of view. Geometric distortion in three dimensions can be characterized by the positional deviations (geometric errors):

$$dx\,(xyz) = x'\,(xyz) - x$$
$$dy\,(xyz) = y'\,(xyz) - y$$
$$dz\,(xyz) = z'\,(xyz) - z$$
$$dr\,(xyz) = \sqrt{dx^2 + dy^2 + dz^2}$$

where x'(x,y,z), y'(x,y,z) and z'(x,y,z) are the coordinates in the distorted space (MR images) and x, y and z are the corresponding coordinates in the undistorted space (CT images). Measures were made to obtain mean values of distortion according to the distance of the center of the field of view.

b) Geometrical distortion linked with magnetic susceptibility and chemical shift

The effect of chemical shift and magnetic susceptibility was evaluated in four healthy volunteers on the above-mentioned Siemens 1.5 T. Magnetom Vision scanner. T_2 weighted Turbo Spin echo sequences (FOV 40x40 cm, 5mm thick contiguous axial slices, 256x256 or 512x512 matrices, $T_R \approx$ 6000 ms, $T_E \approx$ 120 ms, 23 Hz/pixel bandwidth) were used. In the case of a water-fat interface and under the above examination conditions, theoretical shift can be calculated and is close to 15 mm in the frequency encode direction. By swapping over the respective phase encode gradients (PEG) and the FEG, we changed the direction of chemical shift, which it was thus possible to quantify. For each series of images of the above subjects, the outer body, prostate and bladder contours were determined. The centers of gravity of these volumes were computed and their respective distances before and after gradient swap gave the amplitudes of distorsion linked with chemical shift and magnetic susceptibility. The shift of the isocenter determined with three cutaneous markers was determined too. The composition of these markers aimed at minimizing chemical shift; their resonance frequency is inferior to pure water proton resonance frequency. Semi automatic delineation method was used for patient and bladder contour to minimize intra observator variability.

2) Electron densities and planning.

There is no correlation between MR intensities and electron densities. To establish treatment plans on MR alone, this information could be assigned. The feasibility of assigning density to MR images (bone and soft tissues), and how this affects the dose calculation was studied.

CT scans of ten patients with stage T1c - T2c N0M0 prostate cancer were acquired using a Siemens® Somatom Plus (slice thickness 3 mm, matrix size 512x512). Clinical Target Volumes (CTV) (prostate and the base of seminal vesicles) and Organ At Risk (OAR) (bladder, rectum and femoral heads) were delineated by a radiotherapy oncologist. The Planning Target Volume (PTV) included the CTV plus a non uniform 3D margin (anterior, superior and inferior margin : 1 cm ; posterior margin : 0.5 cm). Nine-fields treatment plans (10 or 20 MV) were established on Oncentra Master Plan (Nucletron®). In each patient three dose distribution were compared : original CT, homogeneous density CT and density (bone and soft tissues) assigned CT. In the case of density assigned CT scan, pelvic bones were manually outlined and a 1.2 electronic density relative to water was assigned (data from International Commission on Radiation Units). Water density was assigned to soft tissues. Treatment plans dose matrix were exported and substracted (homogeneous density – original CT and density assigned – original CT). Dose distribution inside PTV, 95 % isodose volume and the proportion of PTV receiving a dose superior to 95 % prescribed dose were compared.

III. RESULTS AND DISCUSSION

1 - Geometrical distortion, chemical shift and magnetic susceptibility

a) Intrinsic geometrical distortion

Mean distortion remained less than, or equal to, 2 mm for a field of view of 20 cm (distance from the center of the field: 10 cm), which concords with the results obtained during the

weekly quality controls of our equipment [6]. This distortion remains less than 3 mm for 45 cm FOV (Figure 1).
These results show that distortion remains at very small values on recent and well-calibrated MRI machines. It would still be possible to make corrections, should they prove necessary, after quality control.
In Tanner *et al.* [1], selected imaging protocol was found to give rise to system distortions of up to 16 mm in the volume corresponding to that used in pelvic imaging. It is important to note that, in the MR scanner used in this study, gradients were unshielded, and according to the authors the use of a more modern MR scanner with shielded gradients and eddy current compensation permits to reduce intrinsic geometrical distortions.

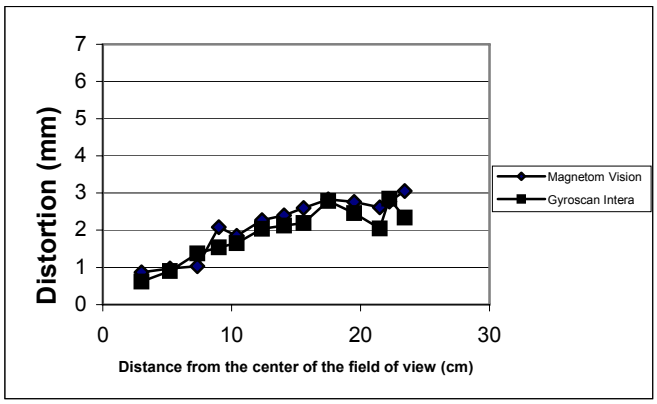

Figure 1. *Distorsion measures on two 1.5 Tesla MR scanners: Magnetom Vision (Siemens®, Erlangen, Germany) and Gyroscan Intera (Philips®, Eindhoven, Netherlands).*

b) Geometrical distortion linked with magnetic susceptibility and chemical shift

The values obtained, ranging from 0.3 to 3 mm, are well below the theoretical values (Table 1). The chemical shift of prostate was too low to be measurable.This result is due to the adaptation of resonance frequency to the subject to obtain maximum radiofrequency reception (maximum difference = 60 Hz between volunteers 1 and 2). The working frequency will thus differ from that of pure water and this adaptation leads to a reduction in the chemical shifts observed. The amplitude of these shifts finally proves to be small and the apparent displacement of a structure such as prostate or bladder in relation to the outer skin contour remains compatible with the precision required for radiotherapy. These shifts should not, however, be completely overlooked when defining external fiducial landmarks useful in positioning the patient. Their composition must be such that their chemical shift is as close as possible to that of the anatomical structures to be considered in treatment planning (target volume, organ at risk, outer contour, etc.). Our markers fulfill these conditions, as the shift of the isocenter determined by three markers was around 1 mm (Table 1).
In Moerland *et al* [2], it was found out that both, chemical shift artefact and magnetic susceptibility artefacts are of the same order, resulting in spatial distortions between –2 and 2 mm in head and neck images. Nevertheless in this study chemical shift was not measured but estimated using the values obtained from the literature. Tanner *et al* [1] have observed in pelvic images a 5 mm shift of a marker relative to the body outline after removing system distortion, due to the summation of contributions from chemical shift and magnetic susceptibility. In our five patients we observed no shift between markers and patient, due to the composition of it. To our knowledge no other author studied the influence of chemical shift and magnetic susceptibility on different pelvic organs. For example Lee *et al.* [5] have estimated this distorsion to 1-3 mm by subtracting an image obtained using a gradient of one polarity from that produced using a gradient of the reverse polarity.

		Subject 1	Subject 2	Subject 3	Subject 4
Outer Contour	Δ x (mm)	1.9	2.5	1.2	2.4
	Δ y	3.5	1.6	2.9	0.6
Bladder	Δ x (mm)	0.4	1	0.3	0.2
	Δ y	0.6	0.8	0.6	1.8
Isocenter	Δ x (mm)	0.2	1.3	0.5	0.1
	Δ y (mm	1.6	0.7	1.8	0.1
Resonance frequency	(Hz)	63 613 **500**	63 613 **560**	63 613 **530**	63 613 **540**

Table 1. *Measurement of chemical shift and magnetic susceptibility in four healthy volunteers.*

2) Electron densities and planning

Using homogeneous CT, PTV underdosage was 2.5 % (10 MV photons) and 1.5 % (20 MV photons). Underdosage was homogeneous inside PTV (SD 0.31 and 0.28) (Table 2). Bone and water density assignment reduced the difference to 0.4 % (±0.2). 95 % isodose volume on homogeneous CT were smaller (-17.5 (± 3.43) %) than on original CT. On density assigned CT, this difference was reduced to 3.01 % (± 3.63). Similarly, density assignment reduced the difference of PTV volume receiving equal or more to 95 % of the prescribed dose from 6.14 % (±3.97) to 0.82 % (±1.25) (Table 2).

	Without heterogeneity correction		With density assignment (soft tissues and bone)
	10 MV	20 MV	
Δ PTV dose	- 2.5 (±0.31) %	- 1.5 (±0.28) %	0.4 (±0.2) %
Δ 95 % isodose volume	- 17.5 (± 3.43) %		3.01 (± 3.63) %
Δ PTV volume receiving >= 95 % prescribed dose	- 6.14 (±3.97) %		0.82 (±1.25) %

Table 2. *Comparison of dose calculation on original CT with homogeneous CT and density assigned CT.*

IV. CONCLUSION

MRI is playing an increasing role in dose planning. The main obstacles are distortion linked with the system and with chemical shift, and lack of information on electron densities. In actual fact, distortion remained low in a volume sufficient for preparing treatment plans, whatever the tumor site (FOV 45 x 45 cm). A distortion correction method could also be applied. Chemical shift and magnetic susceptibility does not appear to affect the accuracy required for radiotherapy, especially if high gradient sequences are used. The assignment of bone electron densities in MR images seems to permit dose planning that is identical with that obtained with CT (Figure 2).

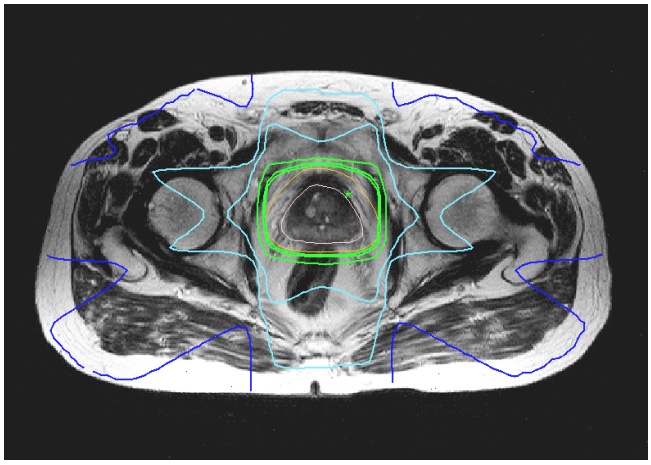

Figure 2. *Treatment planning prepared on MRI alone assigning relative electron densities to soft tissues and bone. From the inside to the outside: Clinical Target Volume, Planning Target Volume, and 95%, 93%, 90 %, 70 %, 50 % and 10% isodoses.*

Similarly, DRR can be produced after the assignment of relative electron densities (Figure 3). The remaining difficulty for many radiation therapy departments is to access to MRI facilities.

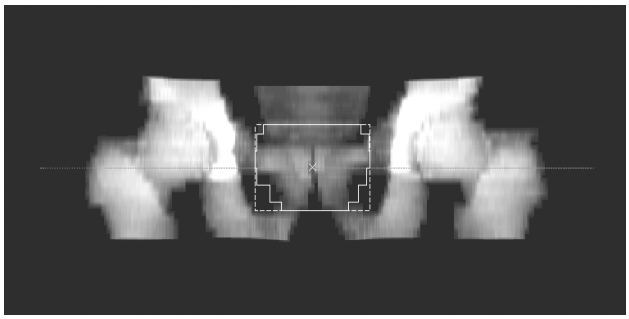

Figure 3. *Digitally Reconstructed Radiographs (DRR) produced by assigning electron densities in MR images.*

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