

Off-line magnetic resonance imaging navigation of cervix cancer brachytherapy in patients with risk factors for uterine perforation

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Abstract

Purpose: There are no reports on pre-insertion identification of cervix cancer patients at risk for uterine perforation during brachytherapy (BT). Our aim was to assess the incidence of risk factors in our patient cohort, and assess feasibility of a novel technique of magnetic resonance imaging (MRI)-guided navigation for applicator insertion (NAI) in high-risk cases.

Material and methods: All patients with locally advanced cervical cancer, treated with image guided adaptive BT at our department between October 2013 and June 2017 were considered for analysis. Tumor characteristics on initial MRI (MRI_{initial}), pre-BT MRI (MRI_{pre-BT}), and BT MRI (MRI_{BT}) were assessed. Frequency of risk factors (age above 60 years, retroverted/retroflexed uterus, tumor necrosis, non-visible cervical orifice, distorted cervical canal) was recorded. Patients with two or more factors underwent MRI guided NAI. Time needed for NAI was estimated and procedure feasibility score assigned using a three-tiered scoring system.

Results: Twenty-seven patients (98 insertions) were included. Mean tumor volume was 70.2 (\pm 47.9), 17.8 (\pm 18.9), and 10.3 (\pm 9.1) cm³ on MRI_{initial}, MRI_{pre-BT}, and MRI_{BT}, respectively ($p < 0.05$). In 16 (59%) cases, ≥ 1 perforation risk factor was found on MRI_{pre-BT}: distorted canal in 12 (44%), necrosis in 9 (33%), retroverted/retroflexed uterus in 8 (30%) cases. Nine (33%) patients had ≥ 2 risk factors and underwent MRI guided NAI. Additional time to perform NAI was estimated at 105 minutes, and feasibility score was 1 in all cases. There were no cases of uterine perforation.

Conclusions: Using pre-insertion MRI, we found ≥ 2 risk factors for uterine perforation in 1/3 of patients. Off-line MRI navigation was feasible and enabled non-complicated insertion in all cases. Further studies with larger sample size are warranted to assess its clinical efficacy.

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Key words: brachytherapy, cervical cancer, cervix cancer, magnetic resonance imaging, uterine perforation.

Purpose

Image-guided adaptive brachytherapy (IGABT) is becoming increasingly adopted as a state of the art treatment component for locally advanced cervical cancer [1,2,3,4,5,6,7]. Accurate placement of applicators in the uterus, vagina, and parametria is required for favorable outcome of IGABT. During dilatation of cervical canal and insertion of the intrauterine tandem, radiation oncologist frequently encounters a challenging patho-anatomical situation. At time of BT, vaginal, cervical, and uterine architecture is commonly disfigured due to residual tumor, necrosis, therapy-induced tissue defects or fibrotic changes. In addition, bleeding or narrow vaginal anatomy can impede identification of external cervical orifice. These findings, especially when combined with posteriorly or

laterally inclined and/or thin-walled uterus, increase the risk of false route and perforation during cervical dilatation and applicator insertion [8,9].

Uterine perforation with the intracavitary applicator is reported to occur in up to 2-14% of insertions [8,9,10,11]. When unrecognized, it may result in over- and under-irradiation of pelvic organs and the tumor, respectively [10]. This leads to increased chance of radiotherapy side effects and reduced chance of cure [10]. Post-insertion sectional imaging enables identification of applicator false route and helps avoid these consequences [8]. However, prevention of uterine perforations is preferred over their early detection, because it also helps avoid other complications such as bleeding, infection, tumor seeding, delay of treatment, need for second anesthesia, etc. Real-time ultrasound has been recommended by several authors to guide

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the tandem insertion and reduce the risk of perforation [8,11,12,13,14,15,16]. At our department, ultrasound is not readily available in the BT suite. But in 2013, we implemented magnetic resonance imaging (MRI) based IGABT. In addition to MRI at diagnosis and at each BT fraction, pre-BT MRI (MRI_{pre-BT}) is routinely obtained prior to applicator insertion in our practice. We use MRI_{pre-BT} for pre-planning of combined intracavitary/interstitial (IC/IS) implants and off-line navigation of applicator insertion (NAI). The aim of our study was to assess, in our patient cohort, the incidence of risk factors for uterine perforation, which were described by authors before [8,9]. We also aimed to describe and assess feasibility of our innovative pre-planning technique of off-line MRI-guided NAI.

Material and methods

Image data sets of all patients with pathology-proven cervical cancer, treated at our department with MRI-based IGABT between October 2013 and June 2017, were considered for analysis. Our routine imaging and treatment protocol was applied in all cases (Figure 1). Patients with available pre-treatment and pre-BT MRI, and complete medical records were included. This work was approved by the Institutional medical research Centre/Ethical Committee (study number: MRC 17239/17).

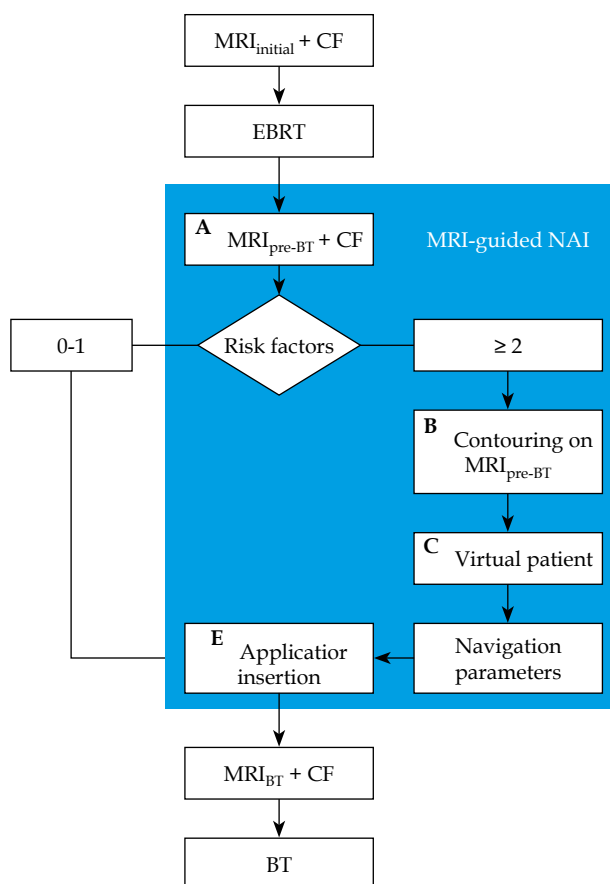


Fig. 1. Outline of our treatment protocol. Blue area (A-E): Magnetic resonance imaging (MRI) -guided navigation of applicator insertion (NAI). EBRT - external beam radiotherapy, BT - brachytherapy, CF - clinical findings

External beam radiotherapy and brachytherapy

External beam radiotherapy (EBRT) planning was based on computed tomography (CT), 18-fluorodeoxy glucose positron emission tomography (18-FDG PET), and MRI simulator. Volumetric modulated arc therapy or 3D conformal radiotherapy was used to apply 45-50.4 Gy in 25-28 daily fractions to the pelvis, with 6 or 15 MV photon beams. In cases considered at high-risk for para-aortic nodal involvement, para-aortic region was treated to 45 Gy. For metastatic pelvic lymph nodes, we aimed to deliver 60-65 Gy, using simultaneous integrated and/or sequential boost [17,18] with 2 Gy per fraction. Metastatic para-aortic lymph nodes were treated with individually adapted boost dose, depending on normal tissue dose constraints. Daily cone beam CT was used for image guidance. Concurrent cisplatin (40 mg/m² per week for 5 weeks) was planned for all patients. Following completion of EBRT, patients were scheduled for 3 (before 2015) or 4 (since 2015) fractions of MRI based IGABT using IC ± IS technique. In our practice, IGABT is performed twice weekly on outpatient basis, and is planned for the 6th and 7th week of treatment, aiming to keep the overall treatment time below 50 days. During BT dose optimization, linear quadratic model with α/β ratio of 10 Gy for tumor and 3 Gy for the organs at risk was applied to calculate the combined (EBRT and BT) biologically equivalent doses in 2 Gy per fraction (EQD₂). While respecting dose constraints for the normal tissues, our planning objective was to deliver a nominal D90 for the high-risk clinical target volume (CTV_{HR}) [19] of ≥ 7 Gy per IGABT fraction. This corresponds to a total EQD2 planning aim (EBRT + BT) of ≥ 85 Gy.

Magnetic resonance imaging technique

Pelvic MRI was scheduled at different points in time (Figure 1): 1) $MRI_{initial}$: prior to treatment start - at EBRT simulation; 2) MRI_{pre-BT} : in 4th or 5th week of EBRT; 3) MRI_{BT} : at each fraction of BT with the applicator in place.

Imaging was performed on a dedicated wide-bore 1.5T 450w MRI simulator (General Electric Optima®, Milwaukee, WI, USA) equipped with radiotherapy applications. Images were acquired using pelvic coils with patient in supine position [20]. For $MRI_{initial}$ and MRI_{pre-BT} , imaging was completed without BT applicator in place. For MRI_{pre-BT} , vaginal walls were unfolded by injecting aqueous gel into the vagina to improve visualization. For MRI_{BT} , the images were acquired after the BT procedure with MRI compatible applicator in place. Our protocol included T2 weighted FSE propeller, diffusion weighted (b values of 150 and 1000), non-contrast enhanced T1 and Dixon type LAVA-Flex sequences. Images were obtained with a slice thickness of 3 mm in para-transverse (perpendicular to cervical canal), para-sagittal, and para-coronal (parallel to cervical canal) orientation. Matrix size was 288 × 288 (para-axial and para-coronal), and 320 × 256 (para-sagittal). The field of view was covering the entire uterus, vagina, and tumor. For the T2 FSE sequence, system related geometric distortions after vendor-provid-

ed correction algorithms are negligible for BT treatment planning, which was confirmed by our recent study [21]. Anonymized MRI data-sets were imported to the treatment planning system (TPS) Brachyvision (Varian, Medical Systems®, Palo Alto, CA, USA) for interpretation and pre-planning.

Interpretation of magnetic resonance imaging and clinical findings

Magnetic resonance imaging was assessed by a senior radiation oncologist, experienced in image guided gynecological radiotherapy. Consultation with radiologist was available in case of equivocal findings. All clinical and imaging findings at diagnosis, before BT and at first BT fraction (BT1), were considered during MRI interpretation (Figure 1) [22]. Size and topography of the tumor, vagina, cervix, uterus, and residual pathological tissues were evaluated. The following details were recorded:

1. MRI_{initial}, MRI_{pre-BT} and MRI_{BT1}: Gross tumor volume (GTV) was contoured using the TPS as the lesion demonstrating hyperintensity signal on T2w FSE sequence [19].
2. MRI_{initial} and MRI_{pre-BT}: The cervico-vaginal and cervico-uterine angles were measured (Figure 2), using the TPS tools.
3. MRI_{pre-BT} and pre-BT clinical examination: The frequency of findings of necrotic areas, non-visible cervical orifice, and distorted cervical canal were recorded (Figure 2). Distorted cervical canal was defined by two or more changes of canal direction or poorly-identifiable lumen.
4. Cone beam CT: When cervico-vaginal and/or cervico-uterine angle on MRI_{pre-BT} was $\geq 180^\circ$ (RVF-retroverted/retroflexed uterus), the changes of uterine position during EBRT were analyzed by reviewing daily cone beam CT images.

Magnetic resonance imaging-guided navigation of applicator insertion

Information from clinical findings, MRI_{initial}, and MRI_{pre-BT} were considered during applicator insertion in all cases. Patients with ≥ 2 risk factors for perforation according to [8] (age above 60 years, uterus in RVF, tumor necrosis, clinically non-visible cervical orifice, distorted cervical canal) underwent systematic MRI-guided NAI. Steps of the NAI pre-planning procedure are outlined in Figure 1. First, the cervix, uterus, vaginal walls, and insertion route (cervico-uterine canal) were contoured on MRI_{pre-BT}. Next, 3D reconstruction of a virtual patient was created using the TPS. In cases with clinically non-visible cervical orifice, the entrance of insertion route was mapped on the surface of the reconstructed cervix in virtual speculum view. This was done by measuring the distances from virtual vaginal fornices to the entry point of the contoured cervical canal. Finally, the insertion route was divided into straight segments. Length and angle of each segment was recorded, and the total length of the insertion route calculated to select the optimal tandem length. Regions of perforation risk were identified and marked on the application route in representative MRI slices and virtual patient views. Insertion of the applicator under anesthesia was scheduled a week after pre-planning. Navigation parameters and visual reconstruction of the application route were followed during the procedure. Time to perform NAI (including pre-BT MRI) was

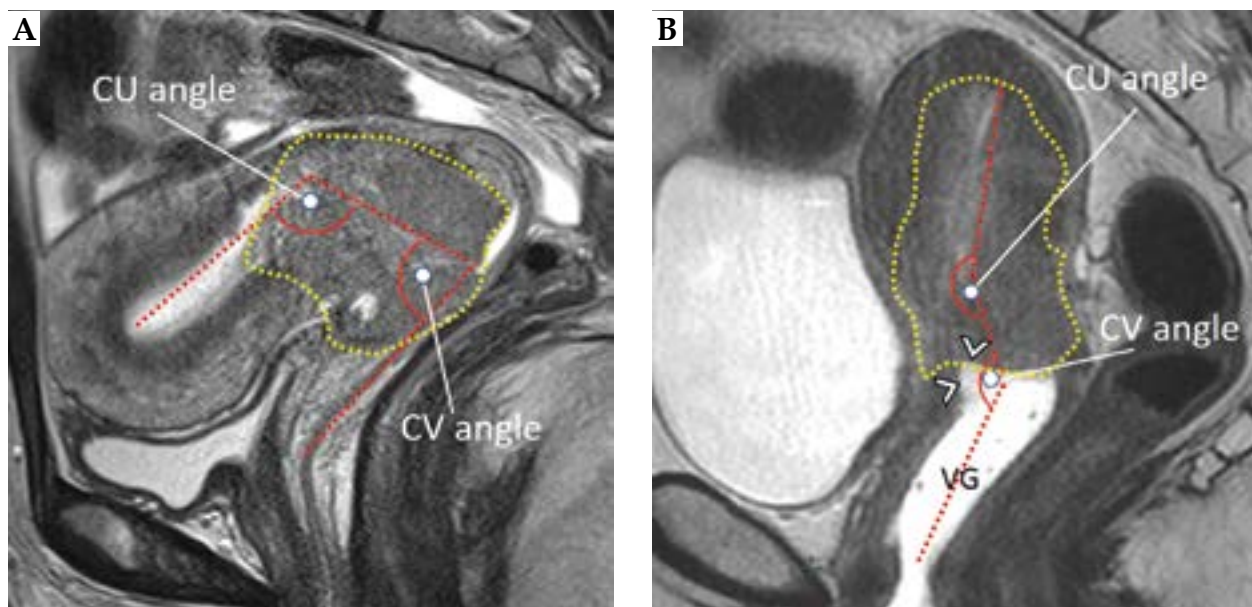


Fig. 2. Schematic representation of cervico-vaginal (CV) and cervico-uterine (CU) angles in two study cases on a sagittal T2w FSE magnetic resonance imaging (MRI). **A)** Initial MRI of a case with angles $< 180^\circ$. **B)** Pre-brachytherapy MRI in a different case with cervico-uterine angle $> 180^\circ$ (retroflexed uterus). Open arrows - necrotic defect. VG - vaginal gel, used to unfold the vaginal walls and improve visualization. Distorted cervical canal was present in this example. Yellow dotted line - gross tumor volume

estimated by the operator. Three-tiered scoring system was used to assess insertion difficulty: 1 - straightforward, non-complicated procedure; 2 - complicated procedure, requiring assistance of radiologist or gynecologist; 3 - procedure terminated due to difficulty or applicator false route.

Statistical analysis

Descriptive statistics were used to present frequencies of categorical tumor characteristics at diagnosis (histology and stage distribution) and pre-BT evaluation (risk factors for perforation). Continuous variables (time intervals, GTV sizes and angles) were presented by mean values with standard deviations. Statistical testing was limited to comparisons of a single variable: mean GTV on MRI_{initial} was compared with MRI_{pre-BT} and MRI_{pre-BT} with MRI_{BT1}. Paired sample *t*-test was used and *p*-value of < 0.05 was considered as the limit for statistical significance.

Table 1. Characteristics of tumors

Tumor characteristic	Number of cases (n)	Proportion (%)
Histopathology		
Squamous carcinoma	24	88.9
Adeno- or adeno-squamous carcinoma	3	11.1
FIGO stage		
IB1-IB2	4	14.8
IIA-IIIB	13	48.1
IIIA-IIIB	6	22.2
IVA-IVB	4	14.8
Maximal tumor diameter		
≥ 50 mm	18	66.7
< 50 mm	9	33.3

FIGO – Federation Internationale de Gynécologie et d'Obstetricque

Table 2. Gross tumor volume (GTV), cervico-vaginal (CV) angle, and cervico-uterine (CU) angle. The differences between GTV sizes were statistically significant (initial magnetic resonance imaging [MRI] vs. pre-brachytherapy [BT] MRI: *p* < 0.01 and pre-BT MRI vs. first BT fraction: *p* = 0.01)

	MRI-based measurement (mean [SD])		
	Initial	Pre-BT	1 st BT fraction
GTV (cm ³)	70.2 (47.9)	17.8 (18.9)	10.3 (9.1)
CV angle (°)	131 (32)	132 (33)	NA
CU angle (°)	169 (44)	175 (54)	NA

NA – not applicable (at BT, angles correspond to applicator geometry)

Results

Patients and tumors

Thirty patients were considered for inclusion in the study. Two were excluded due to incomplete imaging data and one additional case due to non-standard treatment protocol (weekly BT during EBRT). Twenty-seven patients who underwent a total of 98 applicator insertions were eligible for analysis. Median patient age was 43 (range, 32-67) years. Characteristics of tumors at time of diagnosis are summarized in Table 1. The average interval from MRI simulator to EBRT and from pre-BT MRI to BT was 9 (± 7) and 7 (± 5) days, respectively. The interval from MRI simulator to pre-BT MRI was 42 (± 9) days. Mean GTV sizes, cervico-vaginal angles, and cervico-uterine angles are presented in Table 2. GTV reduced significantly during EBRT from 70.2 ± 47.9 cm³ on MRI_{initial} to 17.8 ± 18.9 on MRI_{pre-BT} (*p* < 0.01), and further to 10.3 ± 9.1 cm³ on MRI_{BT1} (*p* = 0.01).

Risk factors for perforation

In 11 (41%) patients, there were no risk factors for perforation on pre-BT assessment. Remaining 16 (59%) cases had at least one risk factor, most commonly distorted cervical canal in 12 (44%), followed by necrosis in 9 (33%), and uterus in RVF in 8 (30%) patients (Figure 3). Inability to identify cervical orifice on pre-BT evaluation and age over 60 years were less common (Figure 3). Among the 8 patients with uterus in RVF position, cervico-uterine and cervico-vaginal angle was ≥ 180° in 8 and 2 cases, respectively (Figure 4). In 6 out of 8 patients with RVF uterus, this finding was depicted already on MRI_{initial}. In remaining 2, cervico-vaginal and/or cervico-uterine angle was less than 180° on MRI_{initial}, but shifted to ≥ 180° on MRI_{pre-BT} (Figure 4). Analysis of daily cone beam CT in these 2 cases revealed that the shift occurred on 18th and 5th fraction of EBRT, respectively. In both cases, the uterus remained in RVF position until the end of treatment. Mean cervico-vaginal and cervico-uterine angles at MRI_{initial} and MRI_{pre-BT} are shown in Table 2.

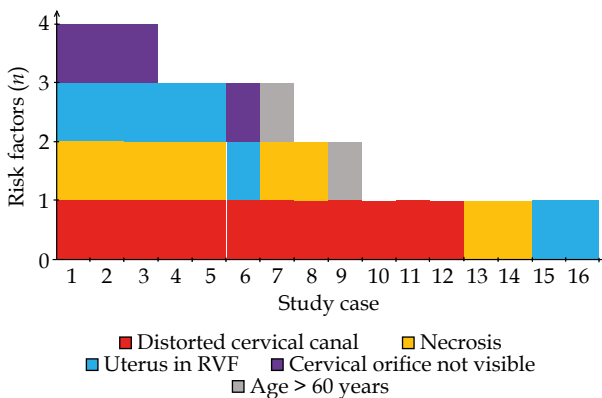


Fig. 3. Distribution of findings in 16 cases with risk factors for perforation on pre-brachytherapy evaluation. RVF – retroversion and/or retroflexion

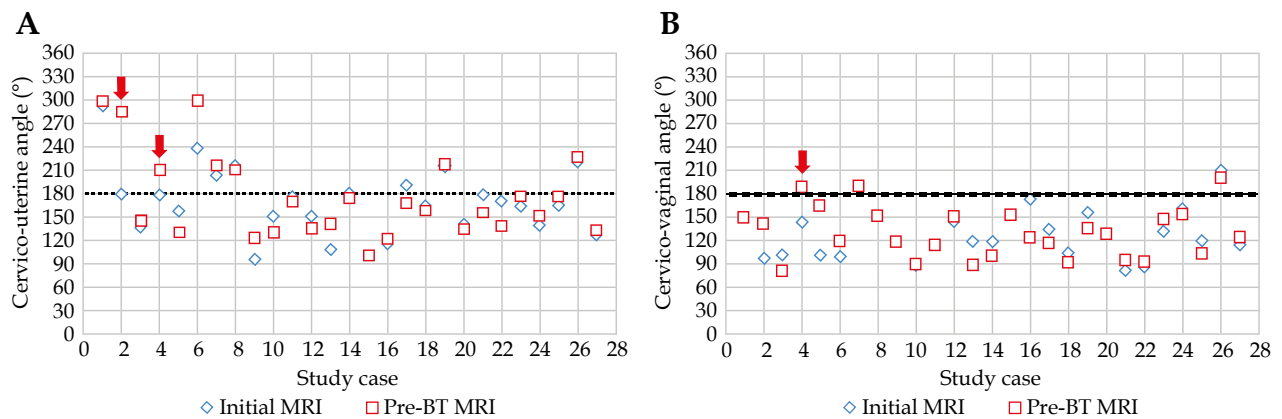


Fig. 4. Cervico-uterine and cervico-vaginal angle in individual study cases, measured from initial and pre-brachytherapy magnetic resonance imaging (MRI). Red arrows mark the cases in which the angle changed from $< 180^\circ$ on initial MRI to $\geq 180^\circ$ on pre-brachytherapy MRI

Feasibility of magnetic resonance imaging-guided navigation for applicator insertion

Nine (33%) patients who presented with ≥ 2 risk factors underwent MRI guided NAI. Systematic use of the navigation parameters increased the operator confidence during applicator insertion. Operator-reported difficulty of NAI-based BT was favorable: applicator insertion was straightforward and non-complicated in all cases (difficulty score 1). Assistance of gynecologist or radiologist was not required in any case. There were no perforations, subserosal insertions or other acute complications of BT procedure. Figure 5 shows the examples of NAI pre-planning in 2 cases. Average additional time required to perform NAI was estimated at 105 minutes. Since off-line MRI guided NAI was performed in parallel with treatment during the 5th week of EBRT, it did not interfere with our routine fractionation schedule and had no impact on the overall treatment time.

Discussion

We reported on the frequency of risk factors for uterine perforation in our patient cohort, based on combined pre-insertion clinical and MRI evaluation. One third of our patients presented with two or more risk factors and consequently underwent systematic MRI guided pre-planning of IC applicator placement. MRI guided NAI was fast and feasible and led to uncomplicated insertion in all cases.

We identified no cases of uterine perforation in our study. Perforation rates prior to implementation of MRI assisted IGABT were not analyzed. It needs to be emphasized that the present study and sample size were not designed to detect the impact of MRI guided navigation on the incidence of these relatively rare, but potentially serious events. The incidence of perforations reported in the literature ranges from approximately 2-14% of insertions in different series [8,9,10,11]. In a recent large mono-institutional report, 428 IGABT procedures in 219 patients were analyzed retrospectively [8]. No pre-planning of IC insertion was performed, but ultrasound guidance

was used in challenging cases. Uterine perforation was identified in 10 (4.6%) patients and 13 (3%) procedures [8]. Bahadur *et al.* recently reported on the incidence of applicator misplacement in a cohort of 82 patients who underwent 231 insertions. Perforation was identified in 12 (14.6%) patients and 14 (6%) applications. Subserosal insertion of the tandem was found in further 12 (14.6%) patients and 20 (8.6%) applications. The authors concluded that the lack of ultrasound guidance in their study was the most likely reason for higher incidence of applicator misplacement [10]. In another report, 124 sequential insertions were performed in 114 patients without pre-insertion imaging or on-line ultrasound guidance. The incidence of perforation, detected on post-insertion CT was 13.7% [9]. Several studies reported on the role of intraoperative ultrasound during BT applications, and this approach is currently considered gold standard for on-line guidance of IC applicator insertion [8,11,12,13,14,15,16]. For difficult or questionable insertions, even direct endoscopic evaluation at the time of tandem insertion was proposed for verification of tandem position [23], but this is not widely used. The need for ultrasound-based real time guidance is especially important in challenging cases with risk factors for perforation. In the study by Segedin *et al.*, the use of intraoperative transabdominal and/or transrectal ultrasound in high-risk patients who had prior perforation, enabled optimal applicator placement on consequent insertions in all cases [8]. Mayr *et al.* reported on 33 ultrasound-guided applicator insertions in 18 patients with retroverted uterus. Anteversion of the inserted tandem and uterus was achieved in all procedures, and there were no cases of perforation [12]. In our present study, there were 8 patients (30 procedures) with the uterus in RVF position on MRI_{pre-BT}. Six out of these 8 patients had two or more accompanying risk factors, most commonly distorted cervical canal and necrosis. Using the information from MRI_{pre-BT} and systematic off-line MRI guided NAI, anteversion of the uterus and optimal applicator placement were achieved in all cases without ultrasound assistance. These results indicate that comprehensive consideration of all imaging and clinical data before the applicator insertion can importantly complement

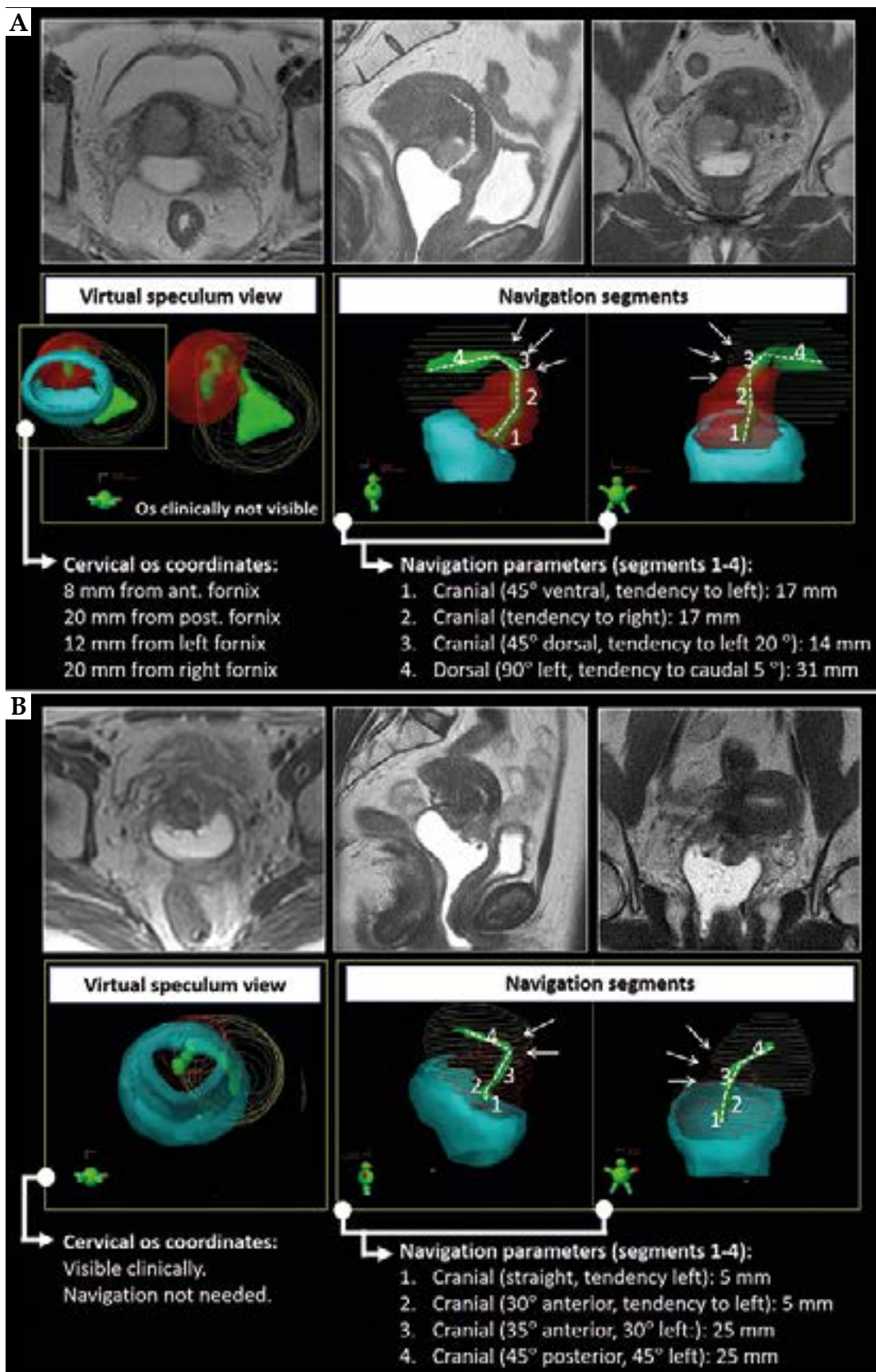


Fig. 5. Magnetic resonance imaging-guided navigation of applicator insertion in two study examples. Yellow – uterus, red – cervix, green – cervico-uterine canal, cyan – vaginal walls, white dotted lines – navigation segments, white arrows – perforation risk

other methods of image guidance, including intraoperative ultrasound. When applied in the systematic context of MRI guided NAI, the pre-planning of IC insertion may even have a potential as an alternative method to on-line guidance. However, this is relevant only for institutions, which have implemented MRI based IGABT, but have limited access to intraoperative ultrasound.

We used information from MRI_{pre-BT} to guide the IC ± IS insertion in all cases. Nevertheless in cases with two or more risk factors for perforation, the formal systematic procedure of MRI guided NAI was followed (Figures 1 and 5). Several studies demonstrated that careful pre-planning of applicator insertion leads to optimal results of gynecological IGABT [24,25,26,27]. Different approaches to pre-planning were described in the literature. Their complexity varies from assessment of pre-treatment MRI alone [24] to geometric and dosimetric pre-planning, based on of pre-BT MRI with the applicator in place [25,26,27]. These methods refer exclusively to individualization of interstitial component of BT applications. The innovative method of off-line MRI guided NAI proposed in our present report enables dedicated off-line pre-planning of IC component. In our experience, off-line MRI guided NAI was fast and feasible, and increased operator confidence during dilatation of cervical canal and applicator insertion. It resulted in optimal placement of IC applicator even in cases with several risk factors for uterine perforation. Radiation oncologist with extensive experience in MRI-guided BT reviewed the MR images in our study, identifying no perforations or subserosal insertions. In view of unequivocal findings in all cases, second opinion from a radiologist was not sought. However, access to consultation with a diagnostic radiologist is strongly advised in clinical practice to minimize uncertainties, especially at an early phase of the IGABT learning curve. The importance of adequate radiology training of oncologists, practicing MRI assisted IGABT, cannot be over-emphasized [22].

Several authors attempted to identify risk factors from post-insertion sectional images with the applicator in place. In the study by Segedin *et al.*, age over 60 years, distorted cervical canal, tumor necrosis, and retroflected uterus were present in 8, 6, 4, and 3 out of 10 patients with perforation, respectively [8]. Combination of two or more of risk factors or age above 60 years was present in 90% of cases with perforation [8]. Barnes *et al.* identified post-insertion physician concern ($p < 0.001$), age greater than or equal to 60 years ($p = 0.0019$), and tumor size ($p = 0.016$) as significant predictors for uterine perforation [9]. In the study by Bahadur *et al.*, stage was the only significant predictor of suboptimal insertion ($p = 0.005$) [10]. Of note, image based assessment of risk factors in these studies was performed only after the applicator insertion. But to reduce the chance of perforation and its negative consequences, pre-insertion identification of patients at risk is required. To our knowledge, our present study is the first to report on a systematic use of MRI_{pre-BT} for pre-operative risk assessment. Some predictors, such as age and tumor stage are readily determined from pre-treatment diagnostic imaging and clinical findings at diagnosis and before BT. However, tumor size and topography, amount

of necrosis and fibrosis, topography of uterus and cervix, changes during EBRT, and the response to treatment differ from patient to patient [24,28,29,30,31]. Therefore, some of the factors that were not present at diagnosis, but became apparent before BT, can be identified only by means of additional pre-insertion imaging. Due its soft-tissue depiction capability, MRI is best suited modality for this purpose.

The risk factors suggested by Segedin *et al.* [8] were used in our study. We found at least one risk factor for uterine perforation in 16 (59%) cases, and two or more factors in 9 (33%) cases on pre-BT evaluation. Necrosis, distorted cervical canal, and retroversion/retroflexion of the uterus were encountered most frequently (Figure 3). The CU and/or CV angle $\geq 180^\circ$ alone or in combination with other risk factors was identified in 8 (30%) of cases. In two of these patients, the uterus was anteverted/anteverted at the start of treatment, but shifted to retroflexion/retroversion during EBRT and remained in this position until the end of BT. These findings underscore the importance of MRI_{pre-BT} for timely identification of unexpected findings at BT. According to our findings, MRI guided NAI could be considered in about one third of patients, if presence of two risk factors was used as the threshold. Setting the threshold at a single risk factor would imply the use of NAI in up to approximately 60% of clinical scenarios. However, the frequencies suggested here must be interpreted with caution because of the small study sample used in our study. Nevertheless, it should be noted that we included all eligible cases treated at our Centre, since implementation of MRI based IGABT in 2013. Furthermore, tumor stages and dimensions at diagnosis and BT, and the pattern of volumetric GTV regression during EBRT (Table 1 and 2) were comparable to reports of others [28]. In summary, our results may be regarded as a proof of concept for MRI-based preoperative assessment of perforation risk and consequent MRI guided NAI in challenging cases. Further analysis of clinical utility and cost-effectiveness of this promising technique, based on a larger number of patients, is warranted.

Conclusions

Pre-brachytherapy MRI enables identification of patients at risk for uterine perforation during cervix cancer BT. Two or more risk factors were found in one third of our patients. Systematic pre-planning of intracavitary insertion with off-line MRI guided navigation is fast and feasible, increases operator confidence during challenging applications, and may reduce the risk of perforation. It can complement the standard approach of on-line guidance with intraoperative ultrasound. Our results may be regarded as a proof of concept regarding feasibility of MRI guided NAI. Further studies are warranted to confirm the potential positive clinical impact of MRI guided navigation on safety of BT applications.

Disclosure

Authors report no conflict of interest.

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