Hysterosalpingography using a flat panel unit: Evaluation and optimization of ovarian radiation dose

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Purpose: The aim of the present study was the evaluation and optimization of radiation dose to the ovaries (D) in hysterosalpingography (HSG).

Methods: The study included a phantom study and a clinical one. In the phantom study, we evaluated imaging results for different geometrical setups and irradiation conditions. In the clinical study, 34 women were assigned into three different fluoroscopy modes and D was estimated with direct cervical TLD measurements.

Results: In the phantom study, we used a source-to-image-distance (SID) of 110 cm and a field diagonal of 48 cm, and thus decreased air KERMA rate (KR) by 19% and 70%, respectively, for beam filtration: 4 mm Al and 0.9 mm Cu (Low dose). The least radiation exposure was accomplished by using the 3.75 pps fluoroscopy mode in conjunction with beam filtration: Low dose. In the clinical study, D normalized to 50 s of fluoroscopy time with a 3.75 pps fluoroscopy mode reached a value of 0.45 ± 0.04 mGy. Observers’ evaluation of diagnostic image quality did not significantly differ for the three different modes of acquisition that were compared.

Conclusions: Digital spot radiographs could be omitted in modern flat panel systems during HSG. Fluoroscopy image acquisitions in a modern flat panel unit at 3.75 pps and a beam filtration of 4 mm Al and 0.9 mm Cu demonstrate acceptable image quality with an average D equal to 0.45 mGy. This value is lower compared to the studied literature. For these reasons, the proposed method may be recommended for routine HSG examination in order to limit radiation exposure to the ovaries.

Key words: hysterosalpingography, flat panel, fluorography, fluoroscopy, radiation dose

I. INTRODUCTION

Hysterosalpingography (HSG) is a radiological procedure that examines the shape of the uterine cavity and confirms fallopian tubes patency in infertility and sterility cases. Imaging of the pelvis is performed with the use of an x-ray unit after the injection of a radio-opaque medium through the cervical canal. The whole HSG examination procedure is described in detail in the work of Simpson et al.1

During the last decade, x-ray units with flat panel (FP) detectors have become available in the market. Compared to standard image intensifier (II) systems, FPs have several advantages such as high sensitivity to x-rays, high spatial resolution, excellent contrast resolution, wide dynamic range, orthogonal field of view (FOV), distortion free images, and relative insensitivity to magnetic field.2 Detective quantum efficiency is higher for the x-ray units with FP compared to those equipped with II, except at low fluoroscopy exposures and specifically when the incident air KERMA (K) to the detector is less than 0.1 μGy per frame.3,4

Since HSG involves direct x-ray irradiation of the pelvis, special concern is raised about the delivered radiation dose to the ovaries (D).5 Last generation digital x-ray units have
already offered reduced radiation dose options without compromising diagnostic image quality. Fluoroscopic images seem to be adequate for the documentation of female genital anatomy and pathology. In radiological procedures with limited motion (such as HSG), modern FP units with the last image—hold feature provide fluoroscopic images of clinically acceptable diagnostic quality, without the additional radiation burden to the patient from single shot exposure images (digital spot fluorography). Besides, modulation of the x-ray spectrum by different combinations of Al and Cu filters at the exit of the x-ray tube as well as proper selection of pulse fluoroscopy mode may further contribute to dose reduction.

The aim of the present study was the evaluation and optimization of $D$ in HSG using appropriately selected geometrical setup and fluoroscopic modes. To this end, a digital x-ray system was configured to irradiate in different fluoroscopy modes in order to assess: (a) contrast-to-noise ratio (CNR), and high contrast spatial resolution (HCSR) for different fluoroscopic and filter modes, and (b) radiation doses to the patient for different fluoroscopic modes.

II. MATERIALS AND METHODS

II.A. System description

A digital x-ray unit with a FP detector (Philips, Allura Xper FD20; Philips Medical Systems, Netherland B.V.) was used. The detector is an indirect FP one that includes a CsI x-ray conversion layer. The elements of the detector are composed of solid state amorphous silicon with a pixel size of 154 $\mu$m$^2$ and the image matrix consists of $2480 \times 1920$ pixels at 14 bit depth. The selectable FOVs in the unit are eight with field diagonal (FD) sizes of 48, 42, 37, 31, 27, 22, 19, and 15 cm.

The unit employs both fluorographic and fluoroscopic modes. Five fluorographic modes are available (6, 3, 2, 1, and 0.5 frames/s), depending on the selected imaging protocol. The filtration during the fluorographic mode is constant and consists of 4 mm Al and 0.1 mm Cu. With regard to fluoroscopy mode, the unit has been initially installed with one irradiation option; 15 pulses per second (pps). After research collaboration with Philips Medical Systems, two additional fluoroscopy pulse rates (7.5 and 3.75 pps) were installed. Every filtration option consists of 4 mm Al and Cu of different thickness. The three available Cu thicknesses are 0.1 [fluoro mode: High dose], 0.4 [fluoro mode: Medium dose], and 0.9 mm [fluoro mode: Low dose].

The unit has an online display for dose evaluation and is capable of summarizing and recording a number of dosimetric related quantities. The printable examination report provides information on the number and kind of operational modes (fluorography and/or fluoroscopy). For each fluoroscopy mode, it provides information on fluoroscopy time, air kerma area product (KAP), K, pulse rate, kVp, mA, filter selection (Al and Cu) and number of recorded fluoroscopic images. For each fluorography mode, it provides information on KAP, K, frame rate, kVp, mAs (per frame), filter selection, and number of recorded fluorographic images. At the end of the examination, the report provides additional information on cumulative fluoroscopy time, total KAP (cumulative fluoroscopic KAP and cumulative fluorographic KAP), cumulative K, as well as total number of recorded fluoroscopic and fluorographic images.

During the acceptance tests and quality control (QC) programs, the measured and displayed values of K rate (KR) have been verified to be within 5% of the reference values mentioned on the unit’s technical specification manual. In addition, the unit is under a periodic QC program based on published protocols in order to ensure the correct performance of the equipment as well as the reliability and reproducibility of exposure parameters.

II.B. Phantom study

A phantom study was conducted aiming to configure the specific geometrical and radiation parameters that would be used in the clinical imaging protocol.

II.B.1. Geometrical configuration

A fixed posterior–anterior (PA) projection geometry has been decided for the whole procedure. The angle, rotation, and angulation of the C-arm with respect to the patient table are shown in Fig. 1. The horizontal level of the table was selected to coincide with the interventional reference point (IRP) which is located along the central ray of the x-ray beam at a distance of 15 cm from the isocenter in the direction of the focal spot. The distance of the IRP from the floor and the focal spot was 91.5 cm and 66 cm, respectively.

The patient was simulated by rectangular blocks of polymethyl methacrylate (PMMA) (Ref. 10) with a total thickness of 20 cm and dimensions of $30 \times 30 \times 1$ cm. The source-to-image-distance (SID) was fixed at the value of 110 cm (see Sec. III). Ideally, the receptor should be positioned near the surface of the pelvis area. During HSG, the patient lies supine with her knees bent, while the soles of her feet rest on the examination table (lithotomy position). The receptor is next to the knees and unavoidably, the value of the SID depends on the patient’s positioning. After the insertion of the speculum and catheterization of the cervix and prior to fluoroscopy, the patients are asked to straighten their knees and keep both legs as close as possible to the surface of the table. In this position, the receptor can approach even further to the surface of the pelvis area, and it is, thus, ensured that the radiation encumbrance due to the SID value is minimized (Fig. 1). In our institution, we only use plastic catheters for HSG examinations as they are both flexible and radiation transparent.

Inappropriate use of FOV significantly increases radiation dose to the patient. Increasing FD from 15 to 48 cm decreases KR by almost a factor of three and increases the total energy imparted by almost a factor of 2. Besides, a bigger FD leads to the radiation exposure of a greater volume of tissue which is apparently unnecessary to reach diagnosis. In the present study, FD was fixed at the value of 48 cm with appropriate use of collimators to image only the anatomical area of interest, aiming to KAP values that are almost equal to those of smallest FD size.
II.B.2. Radiation conditions

The total radiation dose in a radiological examination is the sum of the fluoroscopy and fluorography dose components. Both doses depend on the selected irradiation protocol as well as the total time of irradiation. The aim of any radiation optimization effort is the reduction of the dose in fluorographic and fluoroscopic modes by always taking into account the diagnostic capability of each mode.

Different settings of peak tube voltage, tube current, and pulse duration were explored in a 20 cm PMMA phantom (simulating a normal sized patient) in order to optimize image quality while minimizing radiation exposure to the pelvis. Exposure conditions under investigation involved last-image hold fluoroscopy mode at 3.75, 7.5, and 15 pps. The performance of these different fluoroscopic exposure modes was compared against the gold standard digital spot fluorography mode at 85 kVp and 52 mAs. As far as digital spot imaging is concerned 85 kVp and 52 mAs are the automatically chosen values from the system (Automatic Exposure Control, AEC) with the TOR 18FG (FAXIL, Leeds) positioned in the center of a 20 cm PMMA phantom. Details on the three different fluoroscopic modes under study are outlined in Table I.

In summary, a 20 cm PMMA phantom with SID = 110 cm and FD = 48 cm was irradiated with three different beam filtrations (high, medium, and low dose). The TOR 18FG was positioned in the center of the above-described phantom. The high contrast (HC) area of the object consists of a bar metal pattern with 21 groups of bars representing HCSR values 0.5–5 lp/mm. The low contrast (LC) area of the object consists

<table>
<thead>
<tr>
<th>PMMA exposure conditions</th>
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<tbody>
<tr>
<td>FD</td>
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<tr>
<td>SID</td>
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<tr>
<td>Beam filtration</td>
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<td>Antiscatter grid</td>
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<td>Fluoroscopy modes</td>
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<tr>
<td>Fluorography mode</td>
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</table>
II.C. Clinical study

During a nine-month period, 58 patients were randomly assigned into the three fluoroscopy modes (18 with 15 pps, 18 with 7.5 pps, and 20 with 3.75 pps). Finally, 9 out of 18 (15 pps group), 14 out of 18 (7.5 pps group), and 11 out of 20 (3.75 pps group) were included in our analysis, since only those met the requirements of no angulation of the x-ray unit and $\text{SID} = 110$ cm. The study protocol was approved by our institution’s ethical and research committee, and informed consent was obtained from all patients.

The examination was performed in the first half of the menstrual cycle following cessation of bleeding as described in Ref. 12. This time point facilitates better image interpretation since the endometrium during this phase is thin. The age of the women ranged between 20 and 38 years (mean = 32.3 yr, SD = 5.2 yr). The abdomen thickness in the PA direction was in the range of 14–20 cm (mean = 15.8 cm, SD = 1.6 cm). Mass (M) and height (H) were in the range of 50–80 kg (mean = 62.8 kg, SD = 12.4 kg) and 1.5–1.8 m (mean = 1.64 m, SD = 0.06 m), respectively. The body mass index (BMI) ranged between 17.9 and 32.8 kg/m$^2$ (mean = 23.4 kg/m$^2$, SD = 4.6 kg/m$^2$).

II.C.1. Patient catheterization technique

In order to obtain the necessary parameters for our calculations, four groups of two TLDs were used for each patient. To calculate individualized entrance surface dose (ESD) and $D$, six TLDs were placed in pairs on the back of the patient and one pair of TLDs was placed on the patient’s vagina. $K$ was reported by the x-ray system. To objectively and accurately calculate $D$, TLDs were positioned at the level of the cervix, as this is the closest to the ovaries approachable area. The placement of TLDs at the proximal area of the uterine cervix for the direct measurement of uterus dose is not new. However, questions have risen about the credibility of this technique, since details about stability and sterility of TLDs have not been fully described. In our study, TLDs transfer at the place of interest was accomplished by positioning them in a plastic envelope inside the cup of a syringe. A TLD transfer tool was developed to provide optimum stability and sterility as well as to ensure water-tight environment for TLDs (Fig. 3).

II.C.2. Description of the TLDs transfer tool

A 3 ml syringe was used in the development of the TLDs transfer tool. The barrel of the syringe was removed and the distal external upper parts of the plunger were cut off to develop a uniform cylinder. Consequently, two TLDs were placed on the proximal area of the "modified" plunger prior to the piston and attached with the aid of two-sided tape for optimum stability. This kind of tape was used as it would not leave any adhesive residue after removal for dose measurement. In order to obtain the closest approach to the proximal area of the cervix ostium, the modified syringe carrying the two TLDs was extended with the use of the introduction stabilizer sheath of the HSG catheter. The developed tool was then inserted in a sterile, transparent package, rolled around the longitudinal axis of the tool and stabilized with sterile tapes. With the use of the sterile transparent package and the barrel of the syringe, water-tight environment was ensured during the examination.

II.C.3. HSG specific TLDs calibration

TLDs of lithium fluoride dopped with Mg, Cu, and P [LiF:Mg,Cu,P (TLD100H)] from Harshaw TLD (Bicron, OH) of dimensions $3.2 \times 3.2 \times 0.9$ mm$^3$ were used for radiation
dose measurements. TLDs were calibrated against an ionization chamber (model 10 × 6-6) with an Accu-Pro 9096 control unit (Radcal, Monrovia, CA) in terms of free-in-air geometry using the method reported in Ref. 9.

In order to reproduce the irradiation conditions during HSG in women of medium size (mean weight of 60 kg) under beam filtration: Low dose and 15 pps, we searched our unit’s archive for typical irradiation peak tube voltage and current values. The mean irradiation values were found to be 82 kVp and 14.6 mA. During the calibration of our TLDs, there was the need for reproducing these values. Since the unit works under AEC and the manual irradiation selection is not clinically available, we had to reproduce these values by sequentially placing sheets of Al and Cu at the grid of the FP detector. These sheets were not placed at the exit of the x-ray tube as in such case; the dose at the IRP would not be the same with the dose that women would have received in the same irradiation peak tube voltage and current values.

For TLDs calibration, the previously mentioned spectrum, under free-in-air geometry, was accomplished by positioning 5 mm Cu and 11.5 mm Al at the antiscatter grid entrance of the receptor (KR = 0.142 mGy/s, at SID = 110 cm, FD = 48 cm, beam filtration: Low dose and fluoroscopy mode: 15 pps). The read out of TLDs was made using a manual TLD Reader (Rexon UL-320, REXON TLD Systems & Components, Inc. Beachwood, OH). Prior to each irradiation, all TLDs were annealed at 240 °C for 10 min, followed by fast cooling at 20 °C to optimize their characteristics. Since TLDs do not share the same efficiency, their measured signals differ after irradiation to the same K. A typical batch of TLDs might have a coefficient of variation of 10%–15%. In order to limit this variation, we calculated the individual sensitivity factors of each TLD based on the methodology described in the IAEA calibration protocol.9 Mean values of TLDs were used to calculate ESD and D.

II.D. Image evaluation and reader satisfaction

Evaluation of the phantom study acquired images was based on metrics described below. Diagnostic quality evaluation of patient HSG images was performed with a reader satisfaction survey described in Sec. II.D.2.

II.D.1. Phantom study image evaluation

Acquired image quality was objectively evaluated with the CNR and the HCSR in designated regions of interest (ROI).2,14–17

Briefly, CNR and HCSR are given by the following equations:

\[ \text{CNR} = \frac{|\text{ROI}_1 - \text{ROI}_2|}{\sqrt{\text{SD}_{\text{ROI}_1}^2 + \text{SD}_{\text{ROI}_2}^2}}, \]  

where, ROI\(_1\) refers to the mean value of the pixel content in a selected ROI\(_1\) inside the area of study, and ROI\(_2\) refers to the background mean value of the pixel content in a selected ROI\(_2\) near the area of study, and SD\(_{\text{ROI}_1}\), SD\(_{\text{ROI}_2}\) refer to the standard deviation values for the observed regions.

\[ \text{HCSR} = \frac{\text{SD}_{\text{ROI}_3} - \text{SD}_{\text{ROI}_4}}{\text{SD}_{\text{ROI}_5} - \text{SD}_{\text{ROI}_4}}, \]  

where, SD\(_{\text{ROI}_1}\) is the standard deviation for the pixel content in ROI\(_1\) (ROI\(_1\) refers to the area with f = 1.12 lp/mm at the TOR 18FG), SD\(_{\text{ROI}_4}\) is the standard deviation for the pixel content in ROI\(_4\) (ROI\(_4\) refers to the background mean value of the pixel content in a selected ROI\(_4\)) and SD\(_{\text{ROI}_5}\) refers to the standard deviation for the pixel content in ROI\(_5\) (ROI\(_5\) refers to the area with f = 0.5 lp/mm at the TOR 18FG) (Fig. 4).

ImageJ software, version 1.45s (National Institute of Health) was used to evaluate the images with a personal computer with Intel R Core i7 processor, 2.80 GHz, 8.00 GB of RAM (with a screen resolution of 1900 × 1200 pixels).

Additionally, in order to compare images acquired in the three different fluoroscopy modes a figure of merit (FOM) metric was also incorporated as described in Refs. 16 and 18. More specifically both FOM\(_{\text{CNR}}\) and FOM\(_{\text{HCSR}}\) are given by the following equations:

\[ \text{FOM}_{\text{CNR}} = \frac{\text{CNR}^2}{\text{ESAK}}, \]  

\[ \text{FOM}_{\text{HCSR}} = \frac{\text{HCSR}^2}{\text{ESAK}}, \]  

where, ESAK is the entrance surface air KERMA (with backscatter) at the proximal surface of the PMMA, towards the x-ray tube. ESAK values were measured with the aid of an ionization chamber (model 10 × 6-60) and an Accu-Pro 9096 control unit (RadCal, Monrovia, CA), which was positioned at the level of the IRP. Both FOM\(_{\text{CNR}}\) and FOM\(_{\text{HCSR}}\) have been proposed to determine the x-ray efficiency of the fluoroscopic settings under investigation.19 A FOM is suggested as a measure of image quality per unit radiation dose.20
II.D.2. Reader satisfaction survey

In order to assess HSG image quality for the three different fluoroscopy modes, a reader satisfaction survey was performed. The HSG images from 34 patients were evaluated by two radiologists experienced in performing and interpreting HSG. The radiologists were asked to reply to the following questions in a 1–3 scale (1: no, 2: moderate, 3: yes):

1. Is the uterus cervix contour clearly depicted?
2. Is the uterus contour clearly depicted?
3. Is the fallopian tubes’ lumen clearly depicted?
4. Is the peritoneal contrast spill (when evident) clearly depicted in each side?

II.E. Statistical analysis

Variables are expressed as mean ± standard deviation. Data normality was checked with the Kolmogorov–Smirnov goodness-of-fit test. The Kruskal–Wallis nonparametric form of ANOVA was used to check statistical significance when comparing more than two groups. Whenever this test revealed significant difference, we used Dunn’s post-test to find out the specific pairs that gave rise to that difference. Interobserver variability was evaluated with the nonparametric Wilcoxon test. Statistical analysis was performed with the use of the GraphPad Prim 5 for Windows software (GraphPad Software, Inc. La Jolla, CA). The threshold of statistical significance was set at 5% (p < 0.05).

III. RESULTS

III.A. Phantom study

By changing the SID from 120 cm to 90 cm, the KR measured at the IRP is reduced in accordance to the inverse square law given the same exposure rate on the detector (Table I). After these calculations and taking into account all constraints in patient positioning, a SID = 110 cm was decided for all our subsequent measurements.

The KR was measured in cases of different FD size to assess if the latter can affect radiation burden. The KR values are depicted in Table III, along with the corresponding FOV values. With FD = 48 cm and appropriate use of collimation, the irradiation area is decreased to nearly 50% in order to image only the anatomical area of interest. KR = 0.115 mGy/s at the IRP was measured. KAP rate was found to be 22 mGycm²/s. These values are almost the same with the KAP rate = 24 mGycm²/s measured at FD = 15 cm without collimation applied.

After deciding on SID and FD, images of the PMMA phantom were evaluated for fluorography mode and fluoroscopy mode: 15 pps with beam filtration: High dose to decide which mode would be chosen in the clinical study. As already described in Sec. II, CNR and HCSR metrics were used in the evaluation of the resulting images. More specifically, for fluorography mode K per image was measured 6.09 mGy, while CNR = 2.8 and HCSR = 1.35 were calculated. In the same way for fluoroscopy mode KR was measured 0.517 mGy/s, while K per image = 0.034 mGy, CNR = 3.0, and HCSR = 0.80 were calculated. Based on these values and the fact that fluoroscopy delivers considerably less radiation to the patient, the fluoroscopy mode was decided for all our subsequent measurements.

An additional phantom study was performed to check which combination of fluoroscopy and beam filtration mode is associated with the optimum ratio of image quality metrics (CNR and HCSR) over dose (ESAK). KR, ESAK rate (ESAKR), CNR, HCSR were measured for all fluoroscopy and filtration options. K/image, ESAK/image, FOMCNR, and FOMHCSR values were calculated.

As shown in Table IV, the least radiation burden is achieved with fluoroscopy mode: 3.75 pps and beam filtration: Low dose. CNR values are reported with mean values of 3.0, 2.5, and 1.7 for the High, Medium, and Low dose beam filtration modes, respectively. Based on these CNR values, FOMCNR values were calculated; 205 for High, 223 for Medium, and 241 for Low dose. Additionally, HCSR values are reported with mean values of 0.80 for High, 0.79 for Medium, and 0.77 for Low dose, and the corresponding
TABLE IV. KR, K/image, CNR, FOMCNR, HCSR, and FOMHCSR values for the three different fluoroscopy and filtration modes (SID = 110 cm, FD = 48 cm).

<table>
<thead>
<tr>
<th>Fluoroscopy mode</th>
<th>15 pps</th>
<th>7.5 pps</th>
<th>3.75 pps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Filtration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High dose</td>
<td>74</td>
<td>0.617</td>
<td>0.017</td>
</tr>
<tr>
<td>Medium dose</td>
<td>77</td>
<td>0.517</td>
<td>0.014</td>
</tr>
<tr>
<td>Low dose</td>
<td>83</td>
<td>0.417</td>
<td>0.009</td>
</tr>
</tbody>
</table>

*Mean values for the different fluoroscopy modes.

II.B. Clinical study

Based on the results of the phantom study, the clinical study was performed with the three different fluoroscopy modes, under SID = 110 cm, FD = 48 cm, table at the level of the IRP and beam filtration: Low dose. K, ESD, and D

![Figure 5](image)

**Table V.** K, ESD, and D normalized values for the three different fluoroscopy modes under beam filtration: Low dose.

<table>
<thead>
<tr>
<th>Fluoroscopy mode</th>
<th>15 pps</th>
<th>7.5 pps</th>
<th>3.75 pps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr); mean (SD)</td>
<td>30.6 (3.6)</td>
<td>33.2 (5.7)</td>
<td>32.5 (5.6)</td>
</tr>
<tr>
<td>Weight (kg); mean (SD)</td>
<td>69.4 (16.6)</td>
<td>64.3 (10.8)</td>
<td>65.3 (3.7)</td>
</tr>
<tr>
<td>Height (cm); mean (SD)</td>
<td>166 (4.0)</td>
<td>163 (5.0)</td>
<td>164 (8.0)</td>
</tr>
<tr>
<td>BMI; mean (SD); kg/m²</td>
<td>25.2 (5.9)</td>
<td>24.4 (4.5)</td>
<td>24.6 (3.2)</td>
</tr>
<tr>
<td>PA (cm); mean (SD)</td>
<td>16.3 (2.0)</td>
<td>16.2 (1.5)</td>
<td>16.1 (1.0)</td>
</tr>
<tr>
<td>Examination time (s)</td>
<td>51 ± 21</td>
<td>50 ± 34</td>
<td>50 ± 28</td>
</tr>
<tr>
<td>Knormal (mGy)a</td>
<td>4.92 ± 1.22</td>
<td>2.96 ± 0.75</td>
<td>1.10 ± 0.37</td>
</tr>
<tr>
<td>ESDnormal (mGy)a</td>
<td>7.56 ± 2.40</td>
<td>3.69 ± 0.79</td>
<td>1.64 ± 0.49</td>
</tr>
<tr>
<td>Dnormal (mGy)a</td>
<td>1.68 ± 0.11</td>
<td>1.09 ± 0.07</td>
<td>0.45 ± 0.04</td>
</tr>
</tbody>
</table>

*Reported values are normalized to 50 s of Fluoroscopy time.

FOMHCSR were calculated as 14 for High, 22 for Medium, and 50 for Low dose, respectively. Consequently, the combination of fluoroscopy mode: 3.75 pps with beam filtration: Low dose offers the maximum ratio of both image quality metrics CNR and HCSR over dose (ESAK). Since both FOMCNR and FOMHCSR are suggested as appropriate metrics to evaluate diagnostic images, the combination of fluoroscopy mode: 3.75 pps with beam filtration: Low dose was selected for all subsequent clinical measurements.

III.B. Clinical study

Based on the results of the phantom study, the clinical study was performed with the three different fluoroscopy modes, under SID = 110 cm, FD = 48 cm, table at the level of the IRP and beam filtration: Low dose. K, ESD, and D
were measured for each patient examination. All measurements were normalized to a HSG examination time of 50 s. Table V summarizes acquisition protocol measurements as well as calculated measurements for the three fluoroscopy modes. Analytical measurements are depicted in Fig. 5.

Pairwise statistical comparisons of the normalized data are illustrated in Table VI. All measured values (i.e., K, ESD, and D) showed statistically significant difference between the three investigated fluoroscopy modes, with the 3.75 pps fluoroscopy mode having the least values (Dunn’s post-test). Furthermore, the results of this study for ESD and D values were compared to the available literature (Table VII).

In order to evaluate image findings of the women assigned into the three different fluoroscopy modes, we compared the readers’ scores for each of the four questions asked (Table VIII). No statistically significant difference was found ($p > 0.05$ for each question asked, nonparametric Wilcoxon matched pairs test). Furthermore, we compared the readers’ rankings for each of the four questions asked in order to depict any diagnostic quality difference among the three examined fluoroscopy modes. No statistically significant difference was found ($p > 0.05$ for each question asked, nonparametric Kruskal–Wallis test). Typical HSG images for the three different fluoroscopy modes are depicted in Fig. 6.

### IV. DISCUSSION

In line with the “As Low As Reasonably Achievable (ALARA)” guideline, limiting ionizing radiation exposure aims at the reduction of the delivered dose from fluorographic and fluoroscopic image acquisitions without compromising image quality and diagnostic accuracy. Our results document decrease in radiation burden to the patient compared to already published literature. This is mainly attributed to the fact that we avoided fluorographic images.

Our phantom study revealed that decreasing SIDs leads to radiation burden reduction by 19% (Table II). The KR is 70% lower when a FD of 48 cm instead of 15 cm is used (Table III), while the KAP rate value remains the same with appropriate use of collimators. Collimation during HSG is very important as the imaged (and therefore primarily exposed) body region should be minimized to include only ovaries and uterus. Our diagnostic quality evaluation proved that the fluoroscopy mode ($\text{CNR} = 3.0$, $\text{HCSR} = 0.80$) has adequate diagnostic accuracy compared to fluorography ($\text{CNR} = 2.8$, $\text{HCSR} = 1.35$). We thereby reduced $K$ per frame from 6.09 mGy to 0.034 mGy. In accordance to Gregan et al., when we omitted fluorographic images, we did not lose diagnostic quality (Table VIII, Fig. 6), and we had the major profit of patient’s radiation exposure decrease (Table VIII). These results depict how modern FP units with the last image—hold feature contribute to the decrease of the patient’s radiation burden. Nevertheless, it should be mentioned that examinations that require visualization of clinical features, which are not filled with contrast media, might be CR limited. The low CR limits the extension of the proposed methodology to other dissimilar examinations.

The second part of our study dealt with the issue of decreasing dose during fluoroscopy which has already been discussed in recent literature. To this end, we calculated $\text{FOM}_{\text{CNR}}$ values of 205, 223, and 241 (for High, Medium, and Low dose filtration options, Table IV). In addition, $\text{FOM}_{\text{HCSR}}$ values were 14, 22, and 50 (for High, Medium, and Low dose filtration options). These metrics indicate that the Low dose filtration gives the optimum combination of image quality and dose to the patient.

Our clinical study for the three different fluoroscopy modes under Low dose filtration revealed that $D$ in 3.75 pps mode reached a value of $0.45 \pm 0.04$ mGy (normalized at 50 s fluoroscopy time) during HSG examination. As reported in Table VII, the estimated radiation burden was 0.45 mGy compared to 2.70 mGy in the study of Perisinakis et al., 0.50 mGy in the study of Gregan et al., 4.52 mGy in the study of Calicchia et al., and 4.60 mGy in the study of Fernandez et al. The total radiation burden reduction is mainly attributed to the fact that we did not use fluorographic images.
and the use of a digital unit, where we have the potential of adopting fluoroscopy modes with lower pulse rates combined with the application of beam filtration: Low dose.

For more direct assessment of $D$, we positioned a pair of TLDs next to the patients’ cervix through the vagina as already described in the literature.\textsuperscript{13, 23} This is a limitation of the study as the actual $D$ depends on the size and shape of the patient and the position of the ovaries. As the patient lies supine during HSG, ovaries tend to lie on the retroperitoneum; thus, their level resembles the level of the cervix.\textsuperscript{24} This TLD placement gives a close estimation of $D$ as in this position the TLDs are in approximately the same depth in the PA direction as the ovaries.\textsuperscript{25, 26} Another limitation refers to TLD dosimetry inaccuracies as their efficiency differs within a 10%-15% coefficient of variation which may be minimized though, with the application of proper calibration protocols as in the current study.\textsuperscript{9}

Future prospects of the present work could include efforts to build a mathematical model that could directly translate $K$ values to $D$ with the aid of a number of physical parameters like the backscatter factor, and the patient’s PA distance, thereby avoiding invasive placement of TLDs. Interestingly, applications of the present work can also be extrapolated in other relatively motion-free radiological examinations that permit use of low pulse-rate fluoroscopic acquisitions. This is very critical in special occasions like the pediatric population which is particularly sensitive to ionizing radiation exposure and may benefit the most from similar fluoroscopic acquisition adaptations if feasible. On the other hand, dynamic fluoroscopic acquisitions with limited radiation exposure may also improve the interpretation of tests imaging the gastrointestinal and the urogenital tract that typically exhibit low-motion peristalsis; thus, giving the opportunity to confine the use of digital spot fluorography.

V. CONCLUSIONS

In conclusion, digital spot radiographs could be omitted in modern FP systems when HSG is performed. Fluoroscopy image acquisitions at 3.75 pps and beam filtration: Low dose demonstrate acceptable image quality with an average $D$ equal to 0.45 mGy. This value is lower compared to the studied literature.\textsuperscript{5, 13, 21, 22} For these reasons, the proposed method may be recommended for routine HSG examination in order to limit radiation exposure to the ovaries.

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