Evaluation of a new ultralow-dose radiation protocol for electrophysiological device implantation: A near-zero fluoroscopy approach for device implantation

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BACKGROUND Radiation is one of the main hazards of electrophysiological device implantation, and insertion of cardiac resynchronization therapy (CRT) devices in particular is associated with high radiation doses.

OBJECTIVE The purpose of this study was to evaluate the impact of a new ultralow-dose radiation protocol on radiation doses, success rate, and safety of electrophysiological device implantations.

METHODS In 2018, we established a new ultralow-dose radiation protocol (reduced pulse width, increased thickness of minimum copper filters, reduced detector entrance dose, reduced pulse rate, optimized image postprocessing settings) for de novo device implantation at our hospital. A total of 1173 patients (11% single-chamber devices, 69% dual-chamber devices, 20% CRT devices) were analyzed. Five hundred twelve patients (44%) in the ultralow-dose group were compared to 661 patients (66%) treated during 2017 with a conventional low-dose protocol.

RESULTS With the ultralow-dose radiation protocol, effective doses could be reduced by 59% (median 0.25 [interquartile range: 0.11–0.63] vs median 0.10 [interquartile range: 0.03–0.28] mSv; P < .0001) per procedure without a significant change in procedure time (P = .5). This dose reduction could be achieved without decreasing procedure success (P = 1) or increasing complication rate (P = .8). Male gender, higher body mass index, increased procedure and fluoroscopy times, and use of the conventional radiation protocol were independent predictors of higher radiation doses in multivariate regression analysis.

CONCLUSION By establishing a new ultralow-dose radiation protocol, we could significantly decrease radiation exposure, reaching the lowest radiation doses for electrophysiological device implantation reported to date.

KEYWORDS Cardiac resynchronization therapy; Dose reduction protocol; Implantable cardioverter-defibrillator; Pacemaker; Radiation dose

Radiation exposure is one of the main hazards of electrophysiological device implantation for patients and invasive electrophysiologists. The cumulative low-dose exposure for cardiovascular catheterization staff ranges from 2 to 5 mSv per year and is associated with an increased risk of cancer and cataract.1,2 By using 3-dimensional mapping systems, radiation doses during electrophysiological ablation procedures have been significantly reduced.3 In electrophysiological device implantation, nonfluoroscopic options are uncommon, and cardiac resynchronization therapy (CRT) device implantations in particular are associated with high radiation doses.4 Furthermore, in contrast to ablation procedures, advanced shielding is difficult during implantation procedures, thus underlining the need for alternative modes of radiation dose reduction.

The aim of this study was to evaluate the effect of a new ultralow-dose radiation protocol on radiation exposure and its feasibility and safety during electrophysiological device implantation.

Methods

From January 2018 to April 2018, we established a new ultralow-dose radiation protocol in cooperation with engineers from the manufacturer of the x-ray system (Siemens AG, Erlangen, Germany). Our study focused on patients treated during the months before and after this transition phase.

From January 2017 to January 2019, 1403 patients underwent de novo electrophysiological device implantation (single-chamber, dual-chamber, CRT devices) at our...
institution. Of these patients, 230 were excluded (36 with special device, 186 treated during the transition phase, and 8 with missing data). Therefore, 1173 patients were included for detailed analysis; 661 patients during 2017 (conventional low-dose protocol) served as control group, and 512 patients from May 2018 until January 2019 constituted the ultralow-dose group (Figure 1).

To ensure consistency, all procedures were performed using the same background x-ray settings (see following section) and by the same experienced operators (>200 device implantations per year, >10 years of experience). The study was approved by the institutional ethic committee.

**Background x-ray settings**

Procedures in 2017 were performed with a conventional low-dose imaging program using a floor-mounted Artis zee angiography system (Siemens Healthcare, Erlangen, Germany). The system is equipped with a MEGALIX Cat Plus tube and an as40 flat detector. Cine-loop acquisitions and fluoroscopy were acquired with x-ray tube voltages of 90 and 81 kV, respectively.

All operators aimed to minimize the radiation dose as low as reasonably achievable (ALARA protocol) by using a lower frame rate per second, optimal collimation, minimal magnification, and fluoroscopy instead of cine, and by decreasing the distance between patient and detector.

**New ultralow-dose radiation protocol**

In January 2018, we established an additional, optimized, ultralow-dose radiation protocol consisting of the following steps. For cine-loop acquisitions, pulse width was reduced to 5 ms, and minimum copper filters were set to 0.1 mm. Efficient x-ray dose delivery was primarily enabled by a 5-parameter automatic exposure control (including copper filtration and focus size). Decreased fluoroscopy dose was compensated by optimized image postprocessing settings in order to maintain image quality. An adjusted CLEARmotion postprocessing algorithm (Siemens Healthcare) resulted in noise reduction as well as contrast optimization, due to optimized multiscale signal amplification. The system automatically adjusts the degree of temporal filtration, separately for each pixel. Blurring caused by motion can thus be efficiently reduced. In addition, optimized settings of the CLEARvessel algorithm (Siemens Healthcare) smoothed the image while enhancing the visibility of vessel edges by locally applying spatial noise reduction. Protocols are summarized in Table 1.

**Endpoints**

Radiation exposure was assessed by dose–area products (cGycm²) measured directly by the x-ray system and effective doses (mSv) derived from the dose–area products by multiplying the dose–area product by 0.002. For female
patients, results were multiplied by an additional conversion factor of 1.38 in order to account for their higher biological risk for cancer development through radiation.4

Primary efficacy endpoint was the achieved dose reduction (assessed by dose–area products and effective doses) comparing the conventional low-dose and the ultralow-dose groups. Secondary safety endpoints were success and complication rates in the 2 groups.

Statistical analysis
Stata/SE 12.0 (StataCorp LLC, Texas, USA) and SPSS Statistics 23 (IBM, New York, USA) were used for statistical analyses. Normality test of the variables was accomplished using the Shapiro-Wilk or Kolmogorow-Smirnow test. Normally distributed continuous variables are given as mean ± SD and skewed distributed variables as median with interquartile range (1st and 3rd quartiles). Categorical variables are given as number (percentage). The different groups were compared for clinical and procedural characteristics using the Student t test for normally distributed continuous data. In the case of skewed distributed data, the Mann-Whitney U test was used if there were 2 groups, and the Kruskal-Wallis test was used if there were several groups. The Fisher exact test was used to compare categorical data.

Univariate linear regression analysis was conducted for all independent parameters. In the multivariate model, all variables with \( P \leq 0.05 \) in the univariate models were selected for analysis. \( P \leq 0.05 \) was considered significant.

Results
After a 4-month implementation period (January 2018 to April 2018) of a new ultralow-dose radiation protocol, 512 patients were treated and compared to 661 patients who were treated during 2017 using the conventional low-dose protocol. Clinical and procedural characteristics are listed in Table 2. No statistically significant differences were observed between the 2 groups with respect to age, gender and body mass index (BMI). Single-chamber devices were implanted in 11.5% (9.4% pacemaker, 2.1% implantable cardioverter-defibrillator [ICD]); dual-chamber devices in 68.5% (60.3% pacemaker, 8.3% ICD); and CRT devices in 19.9% (9.5% CRT with pacemaker [CRT-P], 10.4% CRT with defibrillator [CRT-D]) of the 1173 patients, with a significantly reduced number of dual-chamber device implantations in the ultralow-dose group. No differences in procedure and fluoroscopy times were observed except for a reduction in both during implantation of the dual-chamber devices in the ultralow-dose group.

Effective doses (and dose–area products) were significantly reduced in the ultralow-dose group. In total, the median of the effective doses was decreased by 59% (50% in single-chamber devices, 69% in dual-chamber devices, 57% in CRT devices) per procedure (Table 3 and Figure 2). Calculated per minute fluoroscopy time, effective doses were reduced from 0.06 (0.04–0.1) mSv to 0.03 (0.02–0.06) mSv \( (P \leq .0001) \) for single-chamber devices; from 0.06

### Table 1 Imaging settings for conventional-low-dose and ultralow-dose radiation protocols

|                      | Conventional low-dose protocol | Ultralow-dose protocol |
|----------------------|-------------------------------|------------------------|
| Cine                 |                               |                        |
| Cine-loop acquisition dose (nGy/frame) | 120               | 100                    |
| Pulse rate (frames/s) | 10.0                     | 7.5                    |
| Fluoroscopy          |                               |                        |
| Fluoroscopy dose (nGy/frame) | 18.0                | 10.0                   |
| Pulse rate (frames/s) | 2.0                       | 2.0                    |

### Table 2 Clinical and procedural characteristics

|                          | All (n = 1173) | Conventional low-dose protocol (n = 661) | Ultralow-dose protocol (n = 512) | P value |
|--------------------------|---------------|----------------------------------------|---------------------------------|---------|
| Age (years)              | 77 (69-82)    | 77 (69-82)                             | 77 (69-83)                      | .3      |
| Male                     | 726 (62)      | 403 (61)                               | 323 (63)                        | .5      |
| Body mass index (kg/m²)  | 26.6 (24–30)  | 26.6 (24–30)                           | 26.4 (24–29)                    | .7      |
| Device type              |               |                                        |                                 |         |
| Single chamber           | 135 (12)      | 68 (10)                                | 67 (13)                         | .1      |
| Dual chamber             | 804 (69)      | 473 (72)                               | 331 (65)                        | .01     |
| CRT                      | 234 (20)      | 120 (18)                               | 114 (22)                        | .1      |
| Procedure duration* (min)| 35 (25–50)    | 37 (26–50)                             | 35 (25–55)                      | .5      |
| All                      | 26 (20–38)    | 25.5 (20–36)                           | 26 (18–47)                      | .8      |
| Single chamber           | 32 (25–43)    | 34 (25–45)                             | 30 (25–41)                      | .02     |
| CRT                      | 69 (55–90)    | 70 (55–100)                            | 66 (55–82)                      | .2      |
| Fluoroscopy time (min)   |               |                                        |                                 |         |
| All                      | 3.7 (2–7.8)   | 4 (2–7.8)                              | 3.4 (1.9–7.7)                   | .07     |
| Single chamber           | 2.3 (1.2–4)   | 2.55 (1.3–4)                           | 2.2 (1–5.7)                     | .9      |
| Dual chamber             | 3 (1.8–5.1)   | 3.3 (1.9–5.8)                          | 2.7 (1.6–4.7)                   | .002    |
| CRT                      | 13 (7.9–20.6) | 13.8 (8–27.2)                          | 12.4 (7–17)                     | .09     |

Values are given as median (interquartile range) or n (%) unless otherwise indicated.

CRT = cardiac resynchronization therapy.

*Time between skin incision and cutaneous suture.
Effective dose (mSv)

| Group          | Conventional low-dose protocol (n = 661) | Ultralow-dose protocol (n = 512) | P value |
|----------------|-----------------------------------------|---------------------------------|---------|
| All            | 0.25 (0.11–0.63)                        | 0.10 (0.03–0.28)                | <.0001  |
| Single chamber | 0.14 (0.06–0.23)                        | 0.07 (0.02–0.22)                | .007    |
| CRT            | 0.21 (0.10–0.40)                        | 0.06 (0.02–0.16)                | <.0001  |
| Dual chamber   | 0.16 (0.05–0.28)                        | 0.06 (0.02–0.16)                | <.0001  |

By establishing this ultralow-dose protocol in addition to ALARA principles, we were able to reduce radiation doses and reached, to the best of our knowledge, the lowest values during fluoroscopy-guided device implantations reported to date. These results were achieved without prolonging procedure durations, increasing complication rates, and decreasing success rates.

Clinical relevance

Medical radiation accounts for the largest portion of radiation exposure in western countries and is ≈ 3 mSv per person per year. Interventional cardiologists and electrophysiologists in particular are affected, with a cumulative dose exposure ranging between 2 and 5 mSv per year. Every 10 mSv of radiation exposure increases the estimated lifetime risk of dying of a fatal cancer by ≈ 0.05% in addition to the background risk of 21%, resulting in an attributable risk of 1 cancer per 2000 exposed people. The risk of developing a fatal or nonfatal cancer is even higher at 0.1% for every 10-mSv effective dose. In a study by Venner et al., the median effective dose of a cardiac electrophysiologist is 4.3 mSv per year. This corresponds to a risk of 1.3 cancers in 100 exposed subjects during a career of 30 years. By using the new ultralow-dose radiation protocol, this risk can be reduced to 0.5 cancer in 100 exposed cardiologists. For patients, estimation of the reduction of malignancy is difficult because their lifetime exposure to fluoroscopy is variable. Nevertheless, the effect in patients is even higher the more complex the procedures are and the more procedures are performed. In addition, the risk of cataract development is significantly increased.

Previous studies

In electrophysiological ablation procedures, the median radiation dose is ≈ 15 mSv for patients and ≈ 40–66 μSv for patients.
Figure 2  Reduction of effective dose after establishment of a new ultralow-dose radiation protocol. Comparison of estimated effective dose (eED) using the new ultralow-dose protocol (striped bars) and the conventional low-dose protocol (median with 1st and 3rd quartiles; shown as eED in mSv). A: Overall reduction. B: Reduction according to device (single chamber, dual chamber, cardiac resynchronization therapy [CRT]). C: Reduction in relation to patient’s body mass index (BMI). Asterisk denotes significant differences in radiation dose between the conventional low-dose and the ultralow-dose protocols.
operators. For single- and dual-chamber pacemaker or ICD implantations, the median radiation dose for patients is ≈4 mSv (range 1.4–17 mSv), increasing to 22 mSv (range 2.2–95 mSv) for CRT implantations. For operators, radiation dose is 1.2 mSv measured at their hand during CRT procedures.

The major cardiovascular societies recommended a number of measures to reduce x-ray doses (eg, optimal collimation, minimal magnification, increased use of fluoroscopy instead of cine, lowering the distance between patient and detector). By implementing these recommendations, a continuous dose reduction has been possible. Further measures include new x-ray technology, reduction of frame rate and peak kilovoltage, copper filtration, lower detector dose, shorter pulse width, selection of a smaller focus and optimized image processing, and removal of the antiscatter grids.

Nonfluoroscopic systems have been introduced in recent years; however, even with short fluoroscopy times radiation exposure was higher than in the current study. Furthermore, nonfluoroscopic systems are not widely available and are associated with high costs. An overview of the recently published radiation doses as both overall effective dose and adapted for fluoroscopy time is shown in Figures 3A and 3B, respectively.

A detailed comparison of the various x-ray systems and settings used in the different studies is given in Supplementary Table S2.

Ultralow-dose radiation program

Compared to other studies, our baseline radiation doses in 2017 were relatively low. This could be attributed mostly to low fluoroscopy times. In cooperation with engineers from the manufacturer of the x-ray system, we established a new ultralow-dose radiation program. Specifications can easily be implemented in the workflow of other hospitals (Table 1) without reduction in image quality, as shown in Figure 4.

By using our ultralow-dose radiation program, median radiation dose could be reduced by 59% per procedure and by 55% per minute. Compared to the lowest values reported by Attanasio et al, this corresponds to a further reduction of 70% for single-chamber devices, 83% for dual-chamber devices, and 59% for CRT device implantations per procedure.

Although we report the x-ray settings for a Siemens device in our ultralow-dose protocol, the settings can be implemented in the x-ray systems of any manufacturer, which also offer postprocessing algorithms (eg, AlluraClarity; Philips Healthcare, Hamburg, Germany). This fact underlines the broad applicability of our new radiation protocol.

Factors increasing radiation dose

In accordance with the results of other studies, we found that higher BMI and longer fluoroscopy time were the main factors predicting the need for higher radiation doses.

In our study, male gender was significantly associated with higher BMI, suggesting that male gender is to be considered a risk factor as well. During longer procedures, a longer fluoroscopy time was needed because of greater complexity, especially during CRT implantations. Importantly, use of the ultralow-dose protocol could significantly decrease radiation doses independent of the device type or BMI, with the exception of single-chamber devices in the latter group. This exception could be explained by the small number of single-chamber device implantations.

Study limitations

First, patients were not randomized. Nevertheless, they were strictly consecutive cases, and patients did not differ significantly with regard to radiation-relevant clinical characteristics. Furthermore, all patients were treated by the same group of experienced operators.

Procedure and fluoroscopy times were significantly shorter during dual-chamber device implantations in the ultralow-dose group. The difference in procedure time between the 2 groups was not that significant. More importantly, it is apparent that procedure time did not increase despite using the ultralow-dose protocol. The reduced fluoroscopy time might be explained by greater awareness regarding radiation exposure. Nevertheless, the scale of dose reduction cannot be explained by the lower fluoroscopy time alone because there was a similar and significant reduction in the radiation doses calculated per minute fluoroscopy time.

Table 4  Univariate and multivariate regression analyses∗

|                      | Univariate regression analysis |          | Multivariate regression analysis |          |
|----------------------|-------------------------------|----------|----------------------------------|----------|
|                      | Coefficient | Standard error | P value | Coefficient | Standard error | P value |
| Age                  | -0.0095     | 0.0031              | .002    | 0.1503      | 0.0442              | .001   |
| Male gender          | 0.1832      | 0.0693              | .008    | 0.0408      | 0.0044              | <.001  |
| BMI                  | 0.049       | 0.0068              | <.001   | 0.0045      | 0.0015              | .002   |
| Procedure duration†  | 0.0294      | 0.001               | <.001   | 0.0924      | 0.0045              | <.001  |
| Fluoroscopy duration | 0.105       | 0.0028              | <.001   | -0.1979     | 0.0433              | <.001  |
| Ultralow-dose protocol | -0.2613     | 0.0676              | <.001   | NS          | NS                  | NS     |

BMI = body mass index.

*Effective dose in mSv as dependent variable.

†Time between skin incision and cutaneous suture.
Figure 3  Overview of estimated effective dose (eED) reported in different studies or calculated from the stated dose–area products in those studies in comparison to values using the ultralow-dose protocol. A: Overall effective doses. B: Adapted for fluoroscopy time: For better comparison between the effective doses of the different studies, effective doses were calculated per minute fluoroscopy time in all studies indicating fluoroscopy time. Striped bars represent studies using a median to summarize the effective doses. Solid bars represent studies using a mean. 1C = single chamber; 2C = dual chamber; CRT = cardiac resynchronization therapy; ICD = implantable cardioverter-defibrillator; PM = pacemaker.
Conclusion
By establishing a new ultralow-dose radiation protocol, radiation dose for electrophysiological device implantation was significantly decreased by ≈60% and reached, to the best of our knowledge, the lowest radiation values reported to date, even compared to nonfluoroscopic implantation techniques.

This protocol can easily be implemented in the workflow of other hospitals and may become standard for implantation procedures.

Appendix
Supplementary data
Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.hrthm.2019.07.031.

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