White paper

OPTIQ – A new approach to image quality and dose in minimally invasive procedures

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Summary

The last decades have seen a dramatic transformation of medical treatments of cardiovascular, neurovascular and oncologic conditions, replacing traditional open surgeries with minimally invasive interventions. Guided by X-ray images, these procedures are performed through a tiny incision to the vascular system, considerably reducing complications and recovery time. While their advantages greatly outweigh the adverse effects of radiation exposure, the latter remains a subject of concern.
The answer to this concern is the smart use of radiation. Following its long tradition of excellence in image quality at ever reduced doses, Siemens Healthineers introduces a novel philosophy of automatic exposure control, replacing the traditional concept of maintaining a constant detector dose. Instead, the new exposure regulation – OPTIQ – aims at maintaining the requested level of visibility of interventional devices and blood vessels, which are the focal points of the procedure.
For every object of interest, for every patient equivalent thickness and every defined situation, it finds and applies the best suitable set of 5 radiation exposure parameters; namely – the tube voltage, tube current, pulse width, focus size and the copper filter thickness, that reach the requested visibility at the lowest possible entrance dose. Additionally, within physical limits, it maintains this visibility at a stable level – not lower and not higher than required by the operator, independent of the patient equivalent thickness and the system's physical parameters. These measures redefine the principle of "as low as reasonably achievable" (ALARA) radiation exposure in a new physically, technically and clinically more exact way, to further reduce radiation dose to the patient.

Introduction

In the early days of radiography, X-ray images were created using photographic films, which operated only within a narrow exposure range. Later, this classic radiation exposure concept was transferred to the flat panel detectors, where a constant detector dose produces a nearly constant level of image noise.
Until now, this concept has dominated the market, where competing systems of angiography imaging vendors adjust from 2 to 4 radiation exposure parameters to maintain a constant detector dose.
With its advanced exposure control (AEC), Siemens Healthineers took the industry-leading approach of adjusting 5 exposure parameters: Automatically adjusted copper filter thickness assists in balancing the amount of low energy X-rays – suppressing them to reduce patient entrance doses, or transmitting when extra image quality was required (Figure 1).
Automatic selection of the focal spot size, up to three available on Siemens Healthineers angiography X-ray tubes, which is exclusive to Siemens Healthineers, balance image sharpness and higher tube currents, thereby producing higher contrasts. The pulse width optimization helps freezing the motion resulting in crisp images.

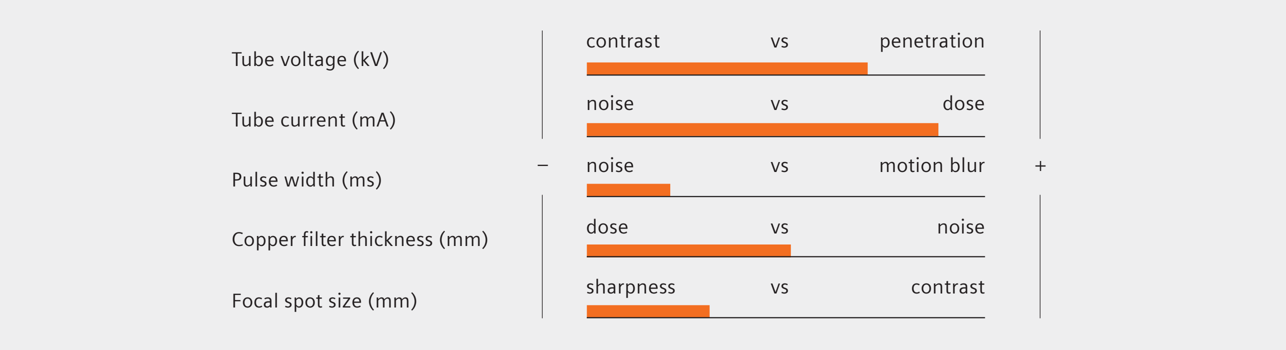


Figure 1:
Exposure parameters adjusting image quality and patient entrance dose. All 5 parameters are inter-dependent, such that modification of any parameter prompts re-adjustment of several others to reach optimum balance of image quality and dose.

Adjustment of the exposure parameters is important for reaching the optimum balance between image quality and dose. Their intricate co-dependence arises due to the limited concentration of the tube power in a focal spot. Even using the Siemens Healthineers tube GIGALIX, having the highest rotation speed and the highest power density among all angiography vendors, patient doses profit from the 5-parameter optimization. A recent study demonstrated the superiority of the 5-parameter exposure control over its older 3-parameter version [1].

An AEC algorithm adjusts the tube parameters according to a specific set of instructions, maintaining the requested detector dose upon changes in the attenuation length. Optimizations of this algorithm for specific clinical procedures are stored in the dedicated organ programs (OGP) in a form of benchmark parameter values (kV, ms, Cu-filter) which define particular states of this algorithm (Figure 2). This brings high flexibility to adapt the AEC for clinical requirements, including the needs of the operating physicians. All these technical complexities are hidden from the operators, who need only to select the OGP dedicated to the procedure at hand.

Patient thickness, source-to-detector (image) distance (SID) and the state of the X-ray beam collimators all affect how many emitted or scattered X-rays reach the detector, which the conventional AEC (both with Siemens Healthineers and other vendors) compensates by adjusting the X-ray intensity, thereby preserving the constant image noise. However, the same factors also affect image contrast, revealing fine image details in some cases and possibly losing them in others. Most importantly, inherent from the constant detector dose, image quality in thicker body regions tend to be lower than in the thinner. While this feature is well understood and sometimes even desired, it may lead to sub-optimum working conditions in some situations, compelling the operator to adjust image quality. With knowledge of these effects, the operators can improve imaging quality on the spot – for example, by collimating the field of view, moving the detector closer to the patient, choosing a different angulation or simply selecting the OGP with the higher detector dose. These manipulations, however, take time and attention of the operator. They also need training and experience.

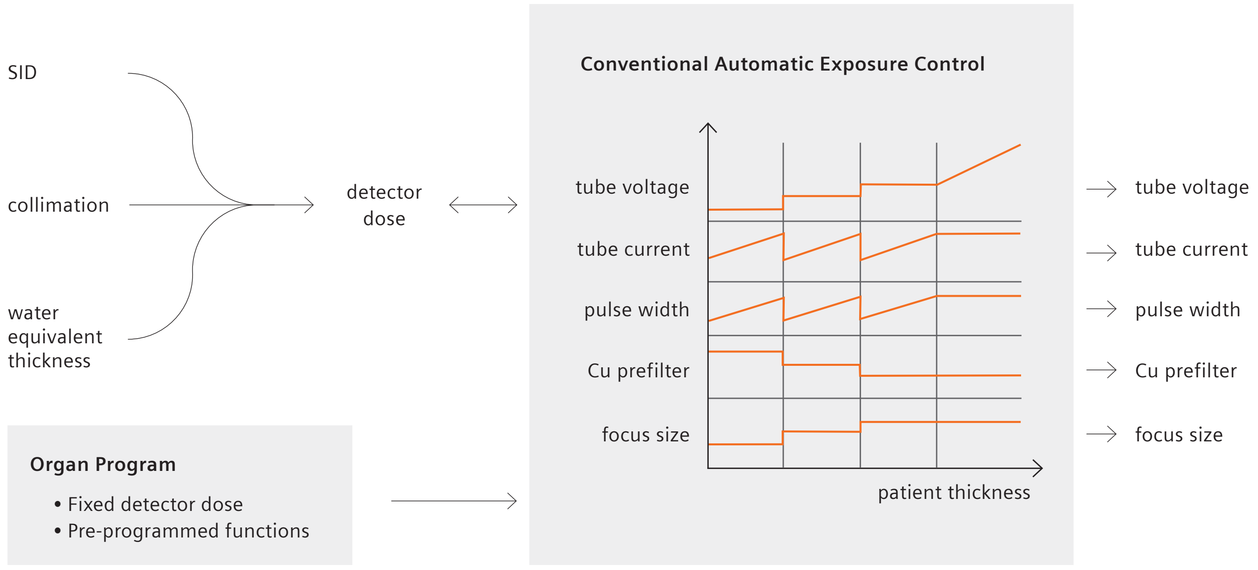


Figure 2:
Conventional advanced exposure control maintains the detector dose upon changes in water equivalent thickness, SID and collimation. It adjusts 5 exposure parameters according to a predefined set of instructions. Organ programs store its various parametrizations in the form of technical parameters which benchmark specific states of the AEC algorithm.

Although the conventional exposure control strikes excellent balance between image quality and patient dose and is constantly proving its industry-leading effectiveness, it has limitations, as no algorithm can take all complexities of X-ray production, scattering and absorption into account. Moreover, clinical disciplines – neuroradiology, cardiology, general interventional radiology, oncology and surgery, representing a vastly diverse and rapidly evolving environment, continuously adopt new procedures and interventional devices with new materials.

Accommodation of the diversifying clinical requirements is only possible through a more comprehensive, analytical approach to image quality and patient dose. The times when the radiology market was dominated by the old idea of maintaining the constant detector dose and controlling the exposure parameters using a fixed instruction set, are coming to an end.

New OPTIQ exposure automatics

Following its tradition of innovation, Siemens Healthineers took a pioneering initiative of redefining the principles of automatic exposure control and rebuilding it from the ground up. The result is a new imaging platform OPTIQ – "Optimal Image Quality". Its philosophy is maintaining the requested stable level of visibility of interventional devices and blood vessels at the lowest possible patient entrance dose. Taking this path required the exact mathematical definition of image quality. This definition focuses on concrete interventional devices and blood vessels, specified by their

- Material (chemical element)
- Characteristic size (spatial frequency)
- Average velocity in a given clinical situation.

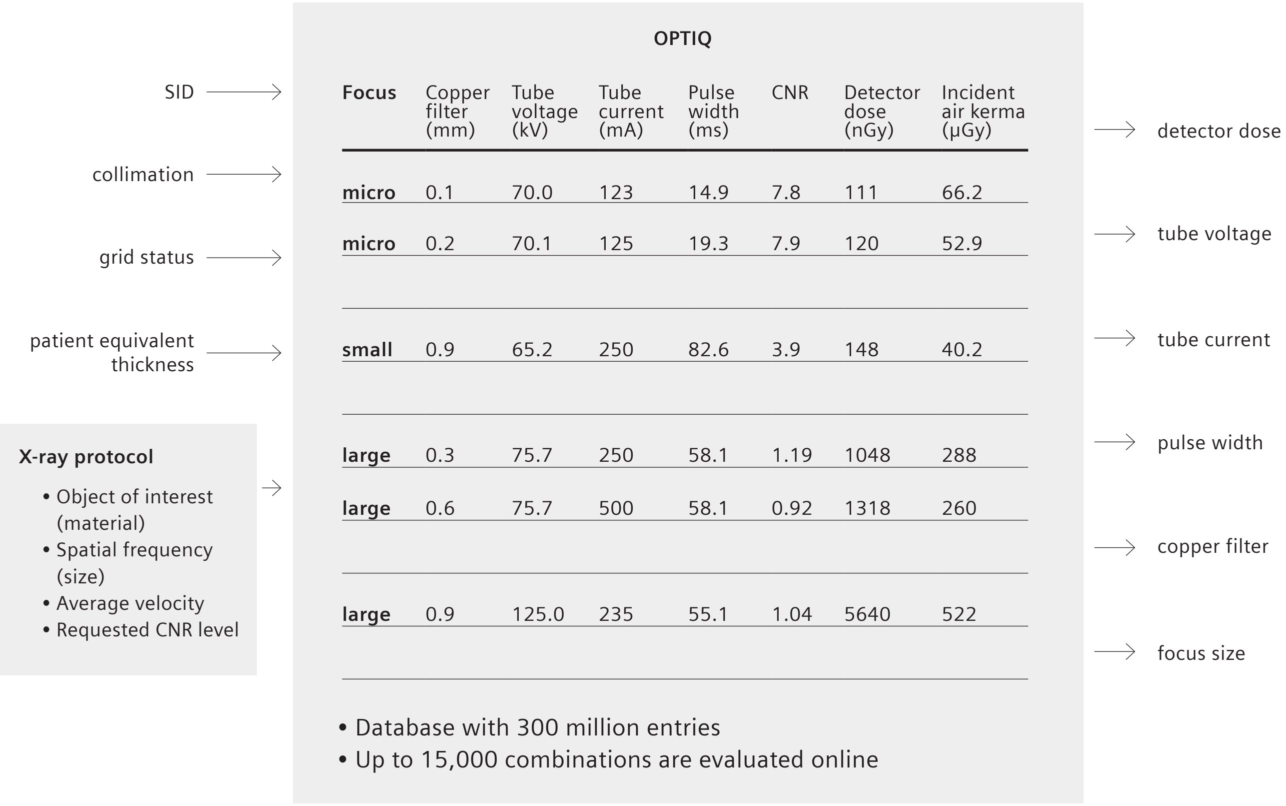
In this way, X-ray protocols – which supersede the organ programs – describe guide wires, catheters, stent struts, radiopaque markers, coils, embolization materials and other interventional devices, as well as blood vessels filled with iodine contrast medium or gas[1]. To each of them, the X-ray protocol attributes a requested level of visibility, defined by the ratio of the contrast they create against the background and the image noise – the contrast-to-noise ratio (CNR). This explicit definition of image quality introduces mathematical accuracy into the automatic exposure control. Now, the task of OPTIQ is to search for the combination of the 5 exposure parameters aiming at the requested CNR and the lowest incident air kerma, which is commonly used as a surrogate of the patient entrance dose.

As with OGP in the previous generation system, the operator of the new system needs only to select the X-ray protocol having image quality optimized for the procedure at hand.[2]

The enabling element of this complex functionality is a vast database containing all possible combinations of the 5 exposure parameters, all materials of interest, and all patient equivalent thicknesses. The latter parameter is an improved alternative to the water equivalent thickness. Patient equivalent thickness refers to the physical thickness along the X-ray path excluding air cavities of a body having chemical element composition identical to the human body. It is assessed by the system via measuring the attenuation of the X-ray beam. The patient equivalent thickness varies continuously with changing angulation and C-arm location. Moreover, the database includes further important parameters – SID, collimation and presence or absence of the grid suppressing the scatter radiation (not available with all angiography system vendors). Their consideration is new and exclusive to OPTIQ.

All possible combinations of the listed parameters amount to 300 million database entries. This database was created using a supercomputer, which modelled the patients' body and all complexities of radiation physics as well as the properties of the X-ray tube and the detector. Each time the operator steps on the foot pedal, OPTIQ evaluates up to 15.000 combinations of the exposure parameters with their pre-calculated CNR and incident air kerma.

It pre-selects this subset of the combinations from the complete database according to the material of interest, measured patient equivalent thickness, as well as the currently selected SID, collimation and the grid insertion status. Among them, OPTIQ selects and applies the optimum combination, reaching exactly the requested visibility of the object of interest at the lowest incident air kerma. Within this system, the detector dose is no longer fixed, but becomes an additional, 6th optimization parameter (Figure 3).



Focus	Copper filter (mm)	Tube voltage (kV)	Tube current (mA)	Pulse width (ms)	CNR	Detector dose (nGy)	Incident air kerma (μGy)
micro	0.1	70.0	123	14.9	7.8	111	66.2
micro	0.2	70.1	125	19.3	7.9	120	52.9
small	0.9	65.2	250	82.6	3.9	148	40.2
large	0.3	75.7	250	58.1	1.19	1048	288
large	0.6	75.7	500	58.1	0.92	1318	260
large	0.9	125.0	235	55.1	1.04	5640	522

- Database with 300 million entries
- Up to 15,000 combinations are evaluated online

The parameter values are given only as an example.
The actual parameters will vary, depending on the clinical situation.

Figure 3:
OPTIQ uses a database of 300 million entries containing all possible combinations of exposure parameters together with CNR and doses they produce in different clinical situations. It adjusts 5 independent exposure parameters and keeps the detector dose variable. X-ray protocols describe the object of interest and its requested CNR. Beside the patient equivalent thickness, OPTIQ takes SID, collimation and the grid status into account.

Constant and flexible image quality

This novel approach brings unprecedented flexibility to image quality. Most importantly, OPTIQ can maintain the constant level of visibility of the devices and vessels independent of the patient equivalent thickness. This level of visibility should be defined by the operators as necessary for a particular clinical task. Through X-ray protocols, different types of tasks can be assigned with different visibility levels, for example stent implantation requiring higher visibility than navigation. It is encouraged to reduce this level to a reasonable minimum that still enables reliably carrying out the task. This should reduce the patients' entrance dose to an "as low as reasonably achievable" (ALARA) dose. By analogy, we call the corresponding visibility level ALARA IQ level.

Maintaining the constant visibility level is new to interventional radiology. It creates more comfortable working conditions where the operators can rely on the system to deliver image quality they request, no matter what patient or clinical situation they encounter (Figure 4). The only limitation here is the patient entrance dose. To minimize the risk of radiation injuries, Siemens Healthineers introduced configurable dose rate limits for both acquisitions and fluoroscopy. The latter can be set equal to or even stricter than the existing legal limit. When the set limit is reached, OPTIQ finds the combination of exposure parameters that maximizes CNR while remaining within this limit. In this regime, the CNR is being reduced with increasing patient equivalent thickness.

A recently published scientific study, performed with phantoms, validated effectiveness of OPTIQ in maintaining constant CNR [2]. It has also demonstrated its high dose reduction potential – producing images of equal or higher CNR at lower incident air kerma.

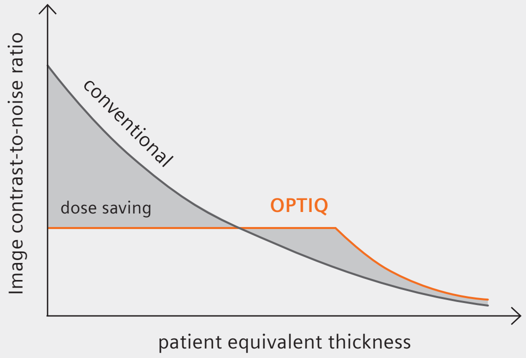


Figure 4:
While conventional exposure controls may have produced images of declining quality, defined by the contrast-to-noise ratio (CNR) with increasing patient equivalent thickness, OPTIQ achieves constant CNR independent of C-arm angulation and patient equivalent thickness – in support of ALARA dose. The dose saving potential in fluoroscopy due to constant CNR of steel and nitinol devices is 55-79% for low attenuations and 10-49% for medium attenuations[3,4].

In thinner body regions, maintaining the constant CNR of steel and nitinol devices in fluoroscopy prevents unnecessary irradiation, potentially saving 55-79 % of the dose at low attenuations and 10-49 % at medium attenuations[3,4]. This is particularly important in treating children. While the constant CNR brings the benefits of low dose, some interventional radiologists might still prefer the conventional approach, producing images of better quality in thinner body regions. If desired, OPTIQ can replicate this functionality with any gradient of CNR level as a function of the patient equivalent thickness. Enhanced visibility of thinner blood vessels in extremities can be one area of its application.

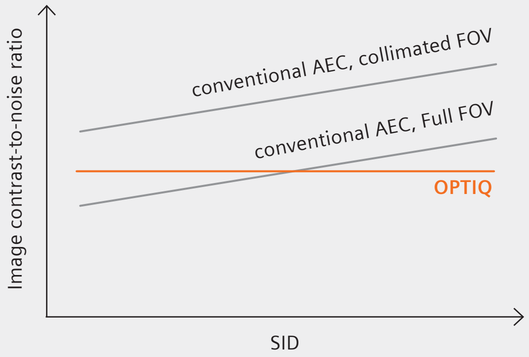


Figure 5:
OPTIQ maintains the requested CNR, stable against variations in SID and collimation of the field of view (FOV), saving the excess patient dose where higher CNR is not needed. Conventional exposure controls could not attain such stability. As OPTIQ adapts to the chosen SID and collimation, it helps the operator to focus on the procedure, saving time and increasing efficiency.

While OPTIQ eliminates the need of manipulating the C-arm to adjust image quality, some system operations are still recommended. For example, collimation of the field of view (FOV) is always advised (now automated within Case Flows on ARTIS icono). It reduces the dose-area-product and the radiation exposure to the operator. Earlier, collimation also increased image quality by lowering the scatter radiation. Increasing the source-to-detector distance also had a similar effect.

With OPTIQ, image CNR will remain constant in both cases, and the system will save the excess dose instead (Figure 5). As a result of these improvements, the operators no longer need to manipulate image quality settings. They now have more time to focus on the clinical procedure at hand.

With the variable detector dose, the noise level of OPTIQ also becomes variable. But at the same time, the contrast follows the noise variation, so that their ratio remains constant, meaning that the number of image details remains preserved. Adaptive image processing, such as intensity windowing, adjusts the images resulting in stable noise and contrast.

Structure Scout

Reaching higher levels of image quality always requires more radiation. As we have shown, OPTIQ is remarkably effective at keeping the image CNR at the fixed level, thereby preventing unnecessary doses. But there are still many possibilities to reach this or any other CNR level: some combinations of the 5 exposure parameters are more efficient at using the radiation than others.

OPTIQ is much smarter at using the radiation than the conventional approach that is the predominant solution in the angiography market today – it reveals same or more details of the object of interest while depositing lower doses. Several factors contribute to its efficiency. The key is the optimization of the energy of X-ray quanta to the absorption properties of the interventional device or contrast media (Figure 6). We call this pioneering functionality Structure Scout, which is part of OPTIQ (Figure 7).

When selecting the following materials in the X-ray protocols, Structure Scout will optimize the visibility of:

- Iron – guide wires, stents, flow diverters and further devices made of stainless steel, nitinol and other alloys of titanium, chromium, manganese, iron, cobalt and nickel
- Iodine – contrast agents, glues, radiopaque additive to catheters
- Tantalum – stent markers, radiopaque additive to Onyx, catheters
- Platinum – stent markers, tips of guide wires, catheters
- Gas – contrast agent CO_2^2
- Barium – contrast agent for the gastrointestinal tract radiopaque additive to catheters

Future system concepts may extend this list to:

- Calcium – bones, plaques
- Gadolinium – contrast agents
- Bismuth – radiopaque additive to catheters

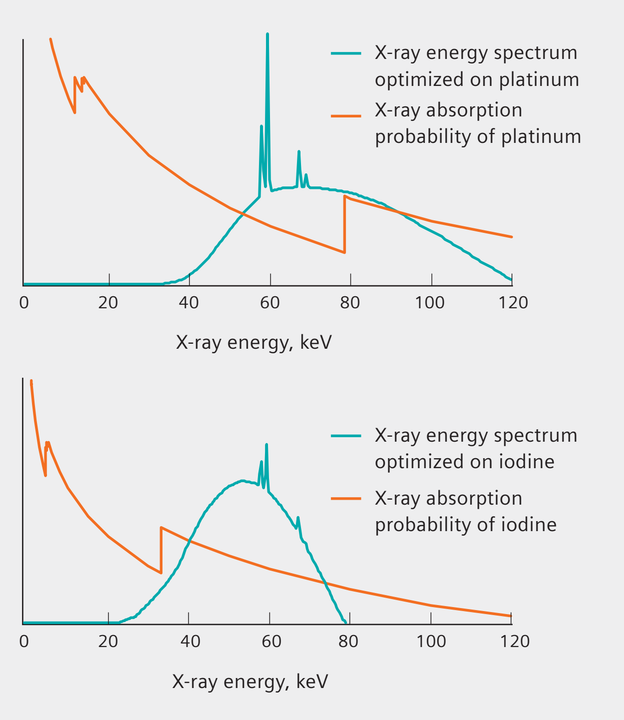
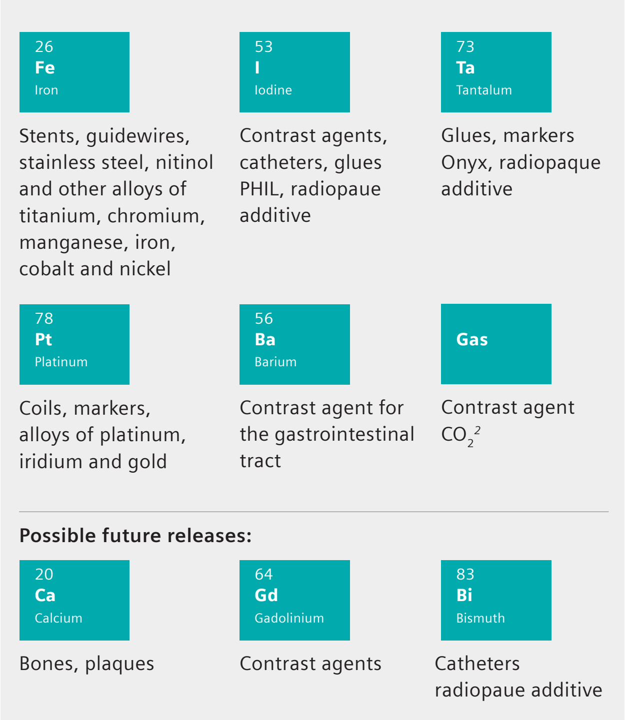


Figure 6:
Material optimization of Structure Scout adjusts the energy spectrum of the X-ray generator for better overlap with the region of high X-ray absorption probability of the material of the interventional device or the contrast medium.



26 **Fe** Iron	53 **I** Iodine	73 **Ta** Tantalum
Stents, guidewires, stainless steel, nitinol and other alloys of titanium, chromium, manganese, iron, cobalt and nickel	Contrast agents, catheters, glues PHIL, radiopaue additive	Glues, markers Onyx, radiopaque additive
78 **Pt** Platinum	56 **Ba** Barium	**Gas**
Coils, markers, alloys of platinum, iridium and gold	Contrast agent for the gastrointestinal tract	Contrast agent CO_2^2

Possible future releases:

20 **Ca** Calcium	64 **Gd** Gadolinium	83 **Bi** Bismuth
Bones, plaques	Contrast agents	Catheters radiopaue additive

Figure 7:
Structure Scout can optimize visibility of human anatomy or materials used in modern interventional devices. The current system focuses on 6 materials; future releases may add further 3 materials.

When two or more materials are simultaneously present in the image, only one of them is enhanced by Structure Scout. Therefore, for the best use of this technology, optimization should be done for the material with the lowest visibility. The other material will still be clearly visible, however not to the system's full potential.

Further optimization features include selection of the correct focal spot for the requested sharpness (spatial frequency) and selection of an adequate pulse width, which freezes the motion of the object of interest with the known average velocity.

But most of its dose efficiency originates from the comprehensive process of selecting the optimum combination of the 5 exposure parameters from up to 15,000 possible combinations.

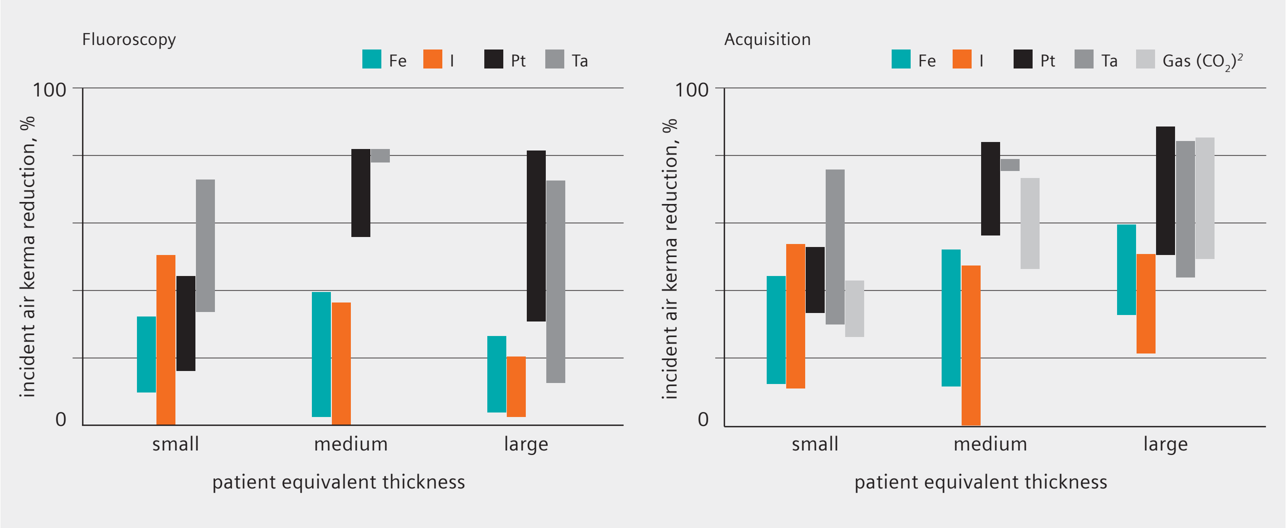


Figure 8:
Phantom measurements indicate that Structure Scout can dramatically reduce incident air kerma, which is commonly used as a surrogate for the patient entrance dose, without reducing CNR. The dose reductions vary with the patient equivalent thickness[4,5,6]. This figure shows the ranges of their variations for small (0 – 19 cm), medium (20 – 29 cm) and large (30 – 40 cm) patient equivalent thicknesses.

Measurements with phantoms revealed how efficient the new OPTIQ with Structure Scout became, in comparison to the previous industry-leading champion – the conventional 5-parameter Siemens Healthineers AEC. When both systems provide identical image quality, defined by the CNR, the new system reduces the entrance dose by 32-83 % during fluoroscopy and by 52-86% during radiography at middle and high attenuations, while maintaining the CNR of platinum[4,6,7]. Similarly, it saves 78-81% of the dose during fluoroscopy and radiography at medium attenuations, while maintaining the CNR of tantalum[4,6,8] and 27-44% during radiography at low attenuations, while maintaining the CNR of CO_2[2,4,6,9] (Figure 8).

Even when imaging ubiquitous iron, OPTIQ reduces the entrance dose by up to 3-27% in fluoroscopy while maintaining its CNR[4,6,10]. When imaging iodine, it reduces the doses by 22-52% during radiography at high attenuations, while maintaining its CNR[4,6,11]. Only for these two materials and at the patients equivalent thickness of about 20 cm, the new regulation provided modest reductions of the doses, confirming excellent optimization of the conventional AEC in this important regime[5].

Structure Scout offers a unique possibility to reduce entrance doses without any degradation of image quality. Its application requires examination of the specific clinical tasks, identifying important devices and vessels which are present, and specifying their parameters in the dedicated X-ray protocols. Since only one device or vessel can be specified, choosing the one with the lowest visibility will make sure that all devices or vessels will be sufficiently visible.

Reducing patient entrance doses is essential for minimizing the probability of radiation injuries, especially for heavy patients, whose skin doses may potentially reach the limits of the deterministic radiation exposure effects. On the other hand, these limits are rarely reached in thinner patients, especially in children.

Children, however, are at higher risk of developing cancer by the direct result of radiation exposure, as the stochastic damage to vital organs have a longer period to manifest. Therefore, minimizing the organ radiation exposure can be a more important strategy for children.

A future version of OPTIQ may look into a possibility to take this optimization strategy. In this case, the system could produce lower energy X-rays that will deposit even lower doses in the inner organs at the expense of slightly higher, but still moderate, entrance doses (Figure 9). An optional further optimization strategy could even minimize radiation exposure of the users.

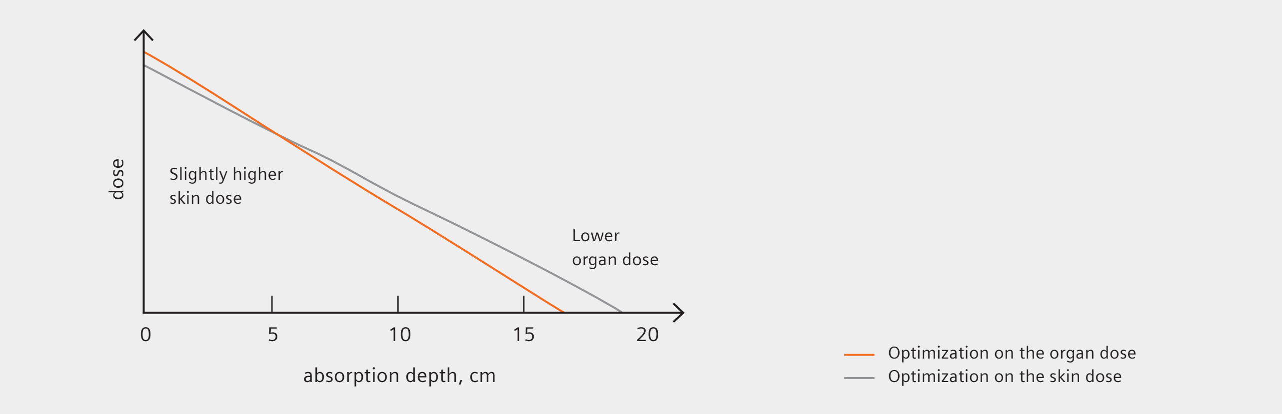


Figure 9:
Future developments of OPTIQ may look into a possibility of introducing additional dose optimization strategies, one of them minimizing doses to inner organs, which might be relevant for children being at higher risk of the stochastic radiation effects.

Conclusions

Rapidly expanding fields of interventional radiology, neuroradiology, cardiology, interventional oncology and image guided surgery request increasingly sophisticated imaging platforms to guide their procedures. Adoption of a variety of interventional devices using new materials applies high and diversified requirements on image quality. At the same time, awareness of adverse effects of radiation exposure applies stronger pressure to reduce patient and operator doses. Within this complex environment, Siemens Healthineers unfolded a new spiral of innovation and introduced a new imaging platform – OPTIQ. Its philosophy is: maintaining the requested stable level of visibility of interventional devices and blood vessels at the ALARA patient entrance dose.

Image quality, or visibility of devices and vessels, is now defined mathematically through the contrast they produce against the background and the image noise as the value of the contrast-to-noise ratio (CNR). Equipped with this explicit definition, OPTIQ reaches the exact CNR level – not lower, but also not higher than requested. The first condition helps the operator to see the devices and vessels reliably in all clinical situations; the second condition prevents unnecessary radiation exposure.

The constant CNR is now maintained independently of the patient equivalent thickness, angulation, collimation and the source-to-detector distance. Apart from reliability and dose benefits, this concept offers more comfort for the operator, who no longer needs to adjust image quality by manipulating with the C-arm, thereby saving time and effort.

The entire engine of the exposure control was rebuilt from the ground up. We introduced a comprehensive search through a database of exposure settings.
This supercomputer-generated database contains 300 million entries of all possible combinations of exposure parameters together with CNR and the doses they produce in different situations. The result is the unprecedented dose efficiency of OPTIQ: it saves significant entrance doses while maintaining the CNR of the common angiography materials[4,5,6]. Never before was the ALARA principle so strictly defined and meticulously applied to every aspect of the imaging system as with OPTIQ – from describing the key image elements, visualizing them with the requested quality in all situations, to optimizing the entire engine of X-ray regulation on the patient dose. With these innovations, OPTIQ introduces a new benchmark in image quality, ease of use and radiation safety.

Scientific proof of OPTIQ

[1] M Dehairs, H Bosmans, W Desmet and N W Marshall, “Evaluation of automatic dose rate control for flat panel imaging using a spatial frequency domain figure of merit”, Phys. Med. Biol. 62, 6610 (2017)

[2] M Dehairs, H Bosmans and N W Marshall, “Implementation of a spatio-temporal figure of merit for new automatic dose rate control regimes in dynamic X-ray imaging”, Phys. Med. Biol. 64, 045001 (2019)

Further publications are planned.

[1] CO_2 is not an approved imaging contrast agent in the USA.

[2] The optimizations were done using mathematical modeling confirmed by phantom experiments.

[3] The constant CNR is achieved within the physical limit of the X-ray tube. The dose reductions were achieved with the CNR-driven exposure control comparing to the detector dose-driven exposure control for the case when 80 nGy/frame yields clinically sufficient CNR at 25 cm patient equivalent thickness. They were obtained using a phantom composed of PMMA and aluminum plates to reproduce X-ray absorption and scattering in 2.5-19 cm and 20-25 cm of patient equivalent thickness, here referred as low and medium attenuations, respectively. Contrast produced by a 0.25 mm thick iron foil, located in the isocenter, and the surrounding noise were measured.

[4] The contrast-to-noise ratio was calculated, considering the contrast-reducing (blurring) effects of the tube focus and object motion. Patient equivalent thickness refers to the physical thickness along the X-ray path excluding air cavities of a body having chemical element composition identical to the human body.

[5] The incident air kerma reductions were obtained using phantom experiments.

[6] The dose reductions were achieved with the CNR-driven exposure control comparing to the detector-driven exposure control.

[7] The dose reductions were obtained using a phantom composed of PMMA and aluminum plates to reproduce X-ray absorption and scattering in 20-40 cm of patient equivalent thickness, here referred as middle and high attenuations. Contrast produced by a 0.01 mm thick platinum foil, located in the isocenter, and the surrounding noise were measured.

[8] The dose reductions were obtained using a phantom composed of PMMA and aluminum plates to reproduce X-ray absorption and scattering in 20-30 cm of patient equivalent thickness, here referred as medium attenuations. Contrast produced by a 0.01 mm thick tantalum foil, located in the isocenter, and the surrounding noise were measured.

[9] The dose reductions were obtained using a phantom composed of PMMA and aluminum plates to reproduce X-ray absorption and scattering in 2.5-20 cm of patient equivalent thickness, here referred as low attenuations. Contrast produced by a 4 mm thick CO2-filled cavity, located in the isocenter, and the surrounding noise were measured.

[10] The dose reductions were obtained using a phantom composed of PMMA and aluminum plates to reproduce X-ray absorption and scattering in 2.5-40 cm of patient equivalent thickness. Contrast produced by a 0.25 mm thick iron foil, located in the isocenter, and the surrounding noise were measured.

[11] The dose reductions were obtained using a phantom composed of PMMA and aluminum plates to reproduce X-ray absorption and scattering in 30-40 cm of patient equivalent thickness, here referred as high attenuations. Contrast produced by a 4 mm thick cavity, filled with iodine-based contrast material, located in the isocenter, and the surrounding noise were measured.

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