Simulation of Internal Backscatter Effects on MTF and SNR of Pixelated Photon-counting Detectors

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ABSTRACT

Properties and performance of digital X-ray detectors for medical imaging can be studied by Monte Carlo simulations. Most simulations of such detectors simplify the setup by only taking the conversion layer into account neglecting everything behind. For hybrid detectors with Si as the conversion layer, such as the Medipix2 chip less photons are absorbed at higher photon energies in the conversion layer and thus may reach the detector ASIC including its bump bonds. For photon energies above the K-edges of the backscatter materials, fluorescence may occur. The fluorescence photons can have relatively long ranges and thus have a great impact on the MTF of the detector decreasing its spatial resolution. They also add noise to the detector decreasing the overall signal-difference-to-noise-ratio (SDNR).

In our study we simulated the line spread functions (LSF) for photon-counting pixel detectors by Monte Carlo simulations, implementing the detectors in detail. We used the program ROSI (ROentgen SImulation) which is based on the well-established EGS4 algorithm. The appropriate MTFs were calculated by FFT.

We show that internal backscattering, especially from Sn bump bonds, contributes to the so-called low-frequency drop of the MTF. For a $300\,\mu$m Si absorber on the Medipix2 chip, backscattering contributes up to $10\,\%$ to the detected signal. This strongly decreases contrast by adding additional noise. Therefore, we also investigated the amount of noise added by internal backscattering.

Keywords: Pixel detectors, photon counting, backscattering, MTF, SDNR, medical imaging

1. INTRODUCTION

In medical X-ray imaging, pixel detectors have become state of the art. In particular, directly absorbing, Se-based detectors with good spatial resolution are used for mammography.[1] The intrinsic limitations of their spatial resolution have been investigated in previous simulations focusing on effects inside the conversion layer.[2] For the sake of simplicity, these simulations neglected all details of the real setup, which consists not only of the conversion layer but also of other components. For the Medipix2 detector an Application-Specific Integrated Circuit (ASIC) is connected to the conversion layer via metallic bump bonds using flip-chip technology. But the approximation of simulating the semiconductor alone can only be used for a conversion material with high absorbance. For higher energies or thinner layers many photons will be transmitted through the conversion layer. These photons can hit whatever is behind the semiconductor layer, e. g. the metal bump bonds mentioned above. The material hit will consequently emit fluorescence quanta. Some of these fluorescence photons will in turn irradiate the conversion layer from behind. Because of their lower energy compared to the incident quanta, they are more likely to be absorbed and detected in the conversion layer. Accordingly, a fraction of the detected radiation originates from photons backscattered inside the detector chip, blurring the image, and deteriorating the spatial resolution. Figure 1 schematically shows such a detector. The output of the detector is a superposition of the primarily detected radiation and the photons originating from fluorescence. In our simulation we investigated the effect of internal backscattering on MTF and SDNR. Therefore, we implemented

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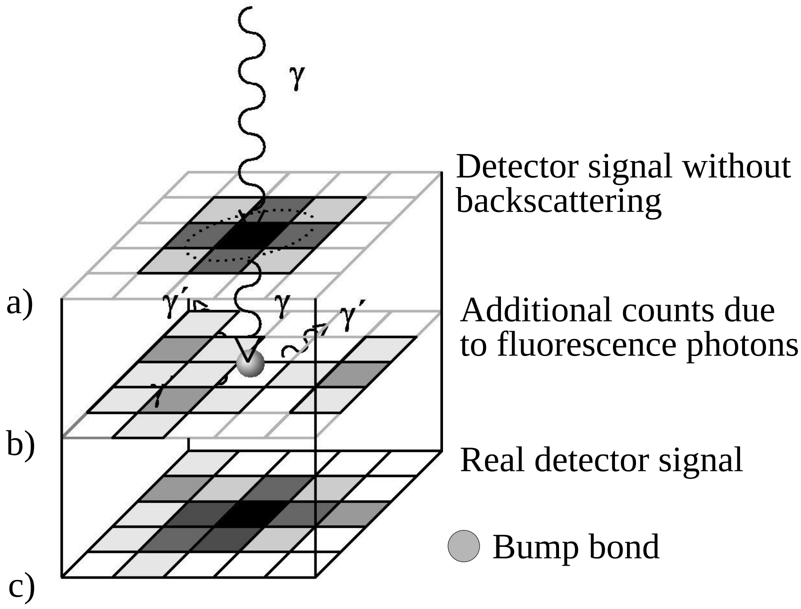

Figure 1. a) A part of the incoming radiation is detected by the semiconductor conversion layer of the detector. Elastic and inelastic scattering as well as charge carrier transport inside the Si- layer leads to a signal blur. For a pencil beam this corresponds to the Point Spread Function PSF. b) Photons which are not absorbed inside the conversion layer can hit the bump bonds. If the energy of these photons is higher than the K-edge of the material (for Sn: 29.2 keV) fluorescence photons are generated and emitted isotropically. Therefore, some of them will hit the conversion layer from behind at locations remote from the position of first incident. Having a lower energy than the incident radiation they are more likely to be absorbed in the conversion layer. c) This leads to additional blurring.

a Medipix2 assembly in all detail which includes all 65,536 bump bonds, the silicon material of the ASIC as well as the ASIC performance. All simulations were carried out with monoenergetic photons. For the simulation of the line spread function (LSF) we used either 25 keV or 30 keV photons, because the K-edge of Sn is in-between (at 29.2 keV).

2. THE SIMULATION

In this study we tackle the problem using Monte Carlo simulations. We used the C++ program ROSI (ROentgen SImulations) by Giersch et al.[3] which is based on the well established EGS4 algorithm. The simulation tool takes into account all electromagnetic interaction and its validity has been proven in many previous applications. For the implementation of the Medipix2 assembly the geometric parameters of the setup were loaded into the simulation. In a first step, we calculated the locations of energy deposition in the material. This energy deposition is represented by a tree of generated electron-hole pairs in the conversion layer. In a second step, the charge carriers are distributed over the detector. In an integrating detector, the signal would be the sum of the collected charge carriers. Since our detector works in counting mode, the pulse height generated by an incident photon has to be compared with a given threshold in every pixel. The output of our simulation corresponds well with the measured output of a Medipix2 assembly.

2.1. The implemented assembly

The detector investigated in this study was an assembly of the Medipix2 ASIC, working in single photon counting mode, bump-bonded, to a $300\,\mu$m Si layer. One ASIC consists of 256×256 pixels with a size of $(55\,\mu\text{m})^2$.
As a semiconductor conversion layer we chose Si with a thickness of $300\,\mu$m, which was also investigated experimentally by our group. The Si layer was connected to the readout chip via bump bonds in flip-chip technology.

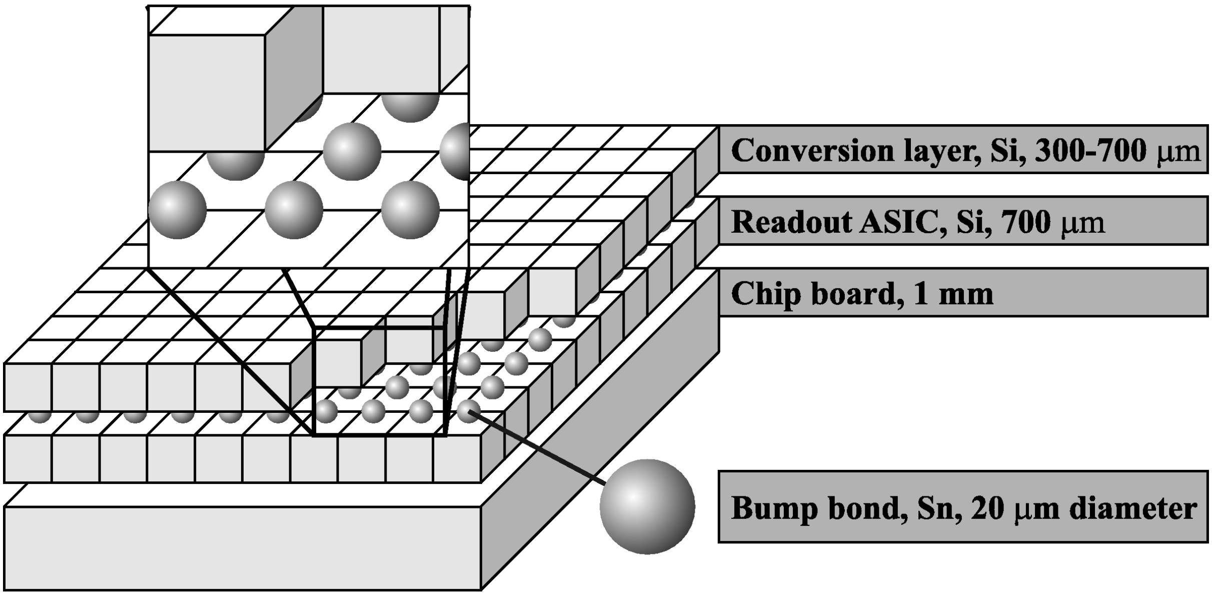

Figure 2. Principal setup of the simulated detector. The semiconductor conversion layer is bump-bonded to the readout chip by flip-chip technology. The chip board is also implemented.

These bump bonds consisted either of a lead-tin compound or, in some cases, just of In. They have a diameter of 20–30 μm. For simplicity we chose pure Sn for the bump bonds. In our simulation every single bump bond was implemented, i. e. 65,536 items had to be simulated, greatly increasing the computation time. So we had to find a compromise between good statistics and a reasonable calculation time. The read-out chip was idealized as a 700 μm Si layer. Further, as in reality, the assembly was mounted on a chipboard. For our simulations we assumed this chip board was a 1 mm thick PMMA layer. Indeed, preliminary simulations showed that the chip board has nearly no impact on the backscattering effects. As long as there are no elements of higher atomic numbers Z in the chip board, it could be neglected. Measurements in our group showed that the glue used for mounting the chip on the chip board can also have an impact on backscattering, because the glue contains silver. Silver-filled epoxy is used to provide good thermal conductivity. A 10 μm thick glue film consisting of 50 % silver will double the number of backscattered photons. The glue was not, however, taken into account in the present simulations. Results on this effect will be published later. The schematic setup is shown in Figure 2.

2.2. Algorithm for the simulation of charge carrier transport and ASIC performance

A known problem of semiconductor detectors is charge sharing. The charge carriers generated in the conversion layer drift in the applied electric field and are collected by the electrodes. Moreover, they can diffuse perpendicular to the electric field. If this effect exceeds the edge of a pixel it can lead to double counts or missed counts, depending on the discriminator threshold, resulting in a major impact on MTF and DQE.

This effect was also included in the simulation. Every charge carrier generated was spatially distributed with a Gaussian probability density function (PDF) with its variance σ^2 depending on the height d in which the electron-hole pair was generated, and on the electrical field E inside the semiconductor.[4]

$$\sigma_r = 23\sqrt{\frac{d\,[\mu\text{m}]}{E\,[\frac{\text{V}}{\mu\text{m}}]}}\ [\mu\text{m}] \tag{1}$$

For the assembly described above with a voltage of 30 V applied to the semiconductor, the variance of the distribution σ_{max}(30V) is 12.6 μm for charge carriers generated at the top of the conversion layer. In typical experiments the voltage is about 100 V leading to a variance $\sigma_{\max}$ (100V) of 6.9 μm. In the simulation we used

a voltage of 30 V in order to show the potentially worst case.
The effect of charge sharing strongly deteriorates the spatial resolution of the detector. In Figure 3 a typical PDF is shown. For an incident photon (compare Fig.3) the energy of the photon is distributed in space. If a pixel is hit near to its edge, some energy is lost to adjacent pixel(s), the so called charge sharing effect.

After calculating the complete charge distribution, every pixel is checked for the amount of energy it has collected. Depending on the threshold, the pixel counts an event or not. For this simulation the threshold was set to 5 keV. This value is low, but clearly above the level of electronic noise of the ASIC. Preliminary simulations showed that the effective pixel size is dependent on the chosen threshold. This could also be confirmed in experiments and will be subject to further investigations.

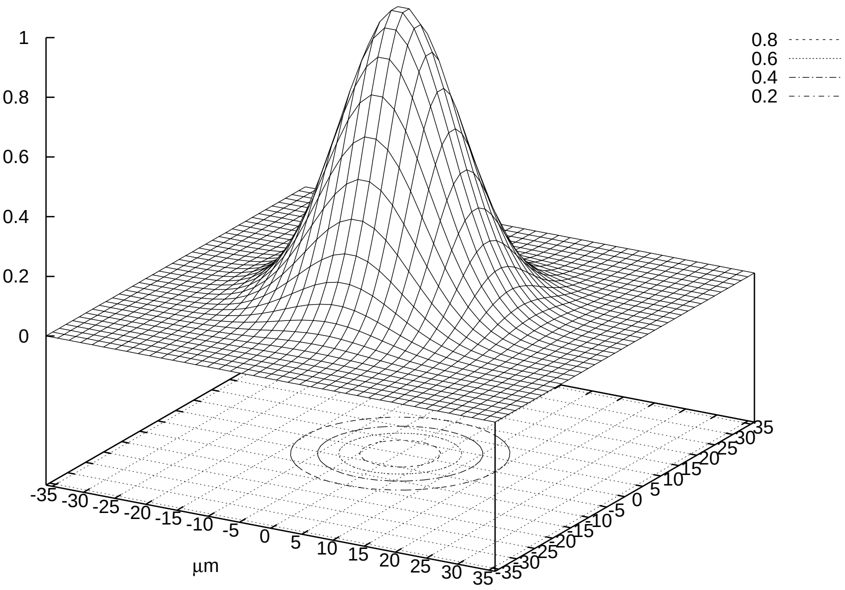

Figure 3. This figure shows one possible PDF for modeling the charge carrier transport inside the semiconductor. The charge is distributed over an area of several μm^2.

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2.3. Simulation of the LSF

One measure for the characterization of detector systems is the MTF. There are three main methods to obtain the MTF, using a slit, an edge or a lead bar pattern phantom. Experimentally, lead bar patterns yield good results. The resulting images can be used to calculate the MTF. For Monte-Carlo simulations these methods are hardly practical because the whole detector has to be illuminated, and consequently, lots of photons are needed, resulting in extremely long computation times because the interaction with matter has to be calculated for each photon separately. So we decided to use the slit method. In order to get the MTF, the Line Spread Function (LSF) of the detector was generated by illuminating the detector with an infinitesimal narrow fan of radiation. The fan beam was slightly (5°) tilted to produce oversampling. The corresponding MTF was calculated via Fast Fourier Transform (FFT). Figure 4 shows a simulated LSF. All simulations were carried out with 10^9 photons.

3. RESULTS AND DISCUSSION

The implementation of the complete assembly in our simulation resulted in additional detected events compared to the simulations with the conversion layer only. Therefore, we calculated how many of the detected events

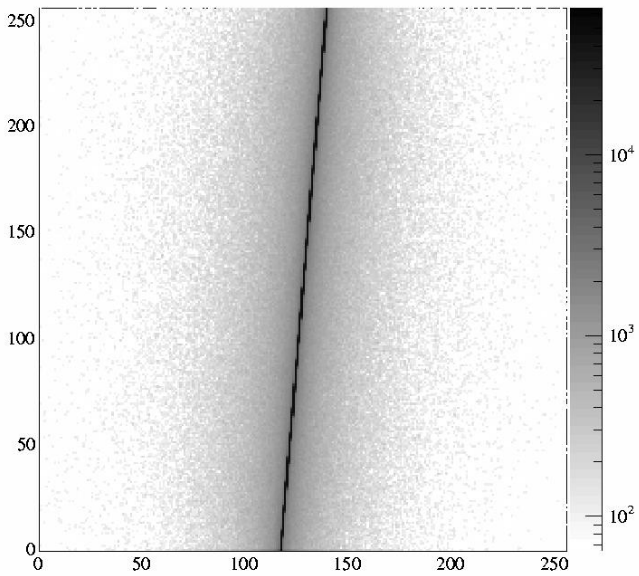

Figure 4. A typical simulated LSF image of a Medipix2 assembly. The LSF image was simulated using 10^9 photons with an energy of 30 keV.

stem from the incident photons and how many stem from backscattering. Image quality and spatial resolution depend directly on these fractions. For energies below the K-edge of Sn (29.2 keV) only a few additional photons are detected. This changes for photon energies above the K-edge. While for the simulation with a photon energy of 25 keV only 0.5 % of the detected events arise from backscattering, this fraction increases to 4.4 % for 30 keV. Calculations show that this fraction increases further for higher photon energies. In Figure 5 the fraction of additional detected events is plotted as a function of photon energy. The sudden rise of additional events at 30 keV indicates that fluorescence of the bump bonds is the main source of backscattered quanta. At higher energies less photons are absorbed by the conversion layer, while the probability of a fluorescence photon being absorbed in the converting layer remains constant. Therefore, fewer detected photons originate from the incident beam, carrying image information. It is obvious that additional detected photons increase the overall signal of the image but will not contribute to the signal difference at higher spatial frequencies of the image. Taking the signal difference to noise ratio (SDNR) as a measure for image quality, one can calculate the loss in image quality. Additional counts lead to a decrease of the SDNR, which is given by

$$\mathrm{SDNR} = \frac{S_A - S_B}{\sqrt{\frac{1}{2}(\sigma_A^2 + \sigma_B^2)}}. \tag{2}$$

Here A and B are regions of interest (ROI) with an average signal S and a variance σ. At a photon energy of 80 keV, 17% of the detector signal consists of additional counts (compare Fig.5) due to fluorescence photons. These backscattered photons can have a range of up to 2 mm which will blur the image. Moreover, not only the amount of additional counts due to fluorescence is of importance but also their spatial correlation. This spatial correlation of the counts introduced by fluorescence photons depends on the locus of incidence of the primary photon and the position of the bump bonds, and leads thus to a deterioration of the spatial resolution of the detector. In order to see the effect of fluorescence photons on the MTF, we concentrated on photon energies slightly above (30 keV) and below (25 keV) the K-edge of Sn (29.2 keV). We simulated the LSFs of the assembly as well as the LSFs for the conversion layer alone and calculated the corresponding MTFs. All simulations were carried out with 10^9 photons. The MTFs computed for simulations of the fully implemented assembly show a low frequency drop (LFD). With a photon energy below the K-edge of Sn, the LFD is only small, while with a photon energy of 30 keV a strong LFD can be observed. In contrast, in the simulations of the conversion layer alone no LFD in the MTF could be observed. Figure 6 shows the calculated MTFs. The sinc function as a theoretical limit for the MTF is also given for comparison. Besides the LFD the calculated MTFs show another interesting feature. The MTFs calculated for the conversion layer alone are neither close to the sinc function, nor do they have the same zero point. In our simulations we find that for a counting detector the shape of the MTF is strongly dependent on the discriminaton threshold energy. The reason is that counting is a non-linear effect. Investigations on this effect are in progress and will be published later.

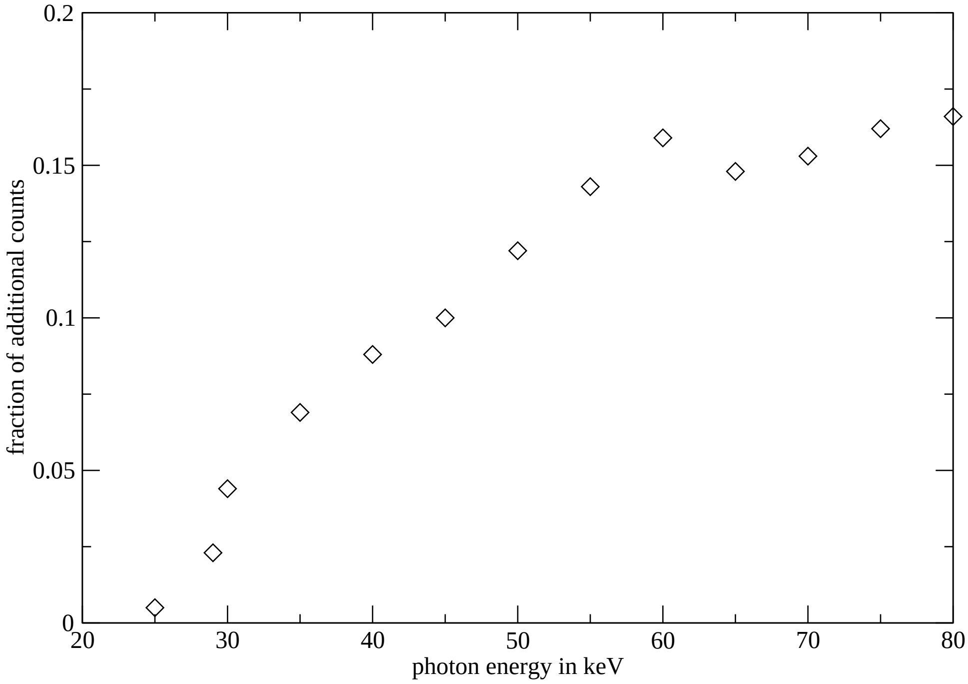

Figure 5. Fraction of additional detected events as a function of the incident photon energy. For higher energies more photons are transmitted through the conversion layer. Therefore, more photons hit the bump bonds and more fluorescence photons are generated.

The observed LFD results from scattering and from fluorescence photons inside the detector. For energies below the K-edge of the bump bonds, no fluorescence photons are generated and the few additional events detected can originate only from elastic or inelastic scattering. But because of the relatively low energy of the backscattered quanta are very unlikely to reach remote pixels. Therefore, most of the scattered photons of a specific bump bond are absorbed by the associated pixel. If the energy of the incident photons is higher than the K-edge of Sn, fluorescence photons are generated ($k_{\alpha_1} = 25.3$ keV). With an attenuation length of 2 mm, these quanta are likely to reach even remote pixels. They are the main reason for the observed LFD.

4. CONCLUSIONS

As a result we found that fluorescence photons generated by the bump bonds of the Medipix detector are one reason for the observed LDF. Our simulations clearly show that not only the interaction inside the conversion layer or charge sharing have an effect on the MTF, but also backscattering and fluorescence from objects behind the sensor layer. This study makes it obvious that the setup behind the converting layer can not be neglected

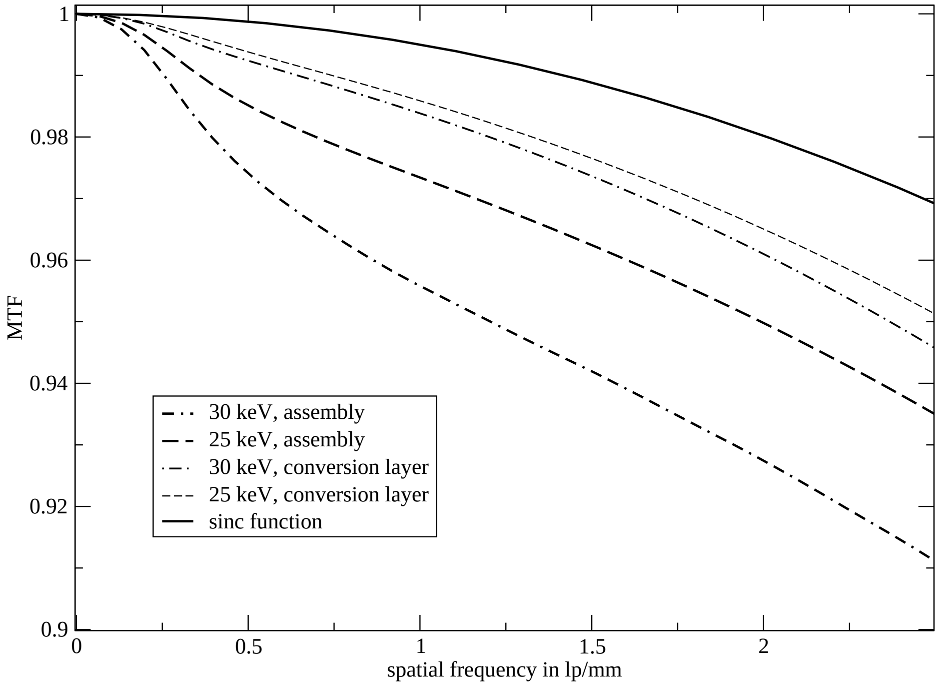

Figure 6. Calculated MTFs as a functions of spatial frequency. All simulations were carried out with 10^9 photons. From the simulation of the assembly a LFD can be obseverd. The sinc function as a upper limit for the MTF is plottet for comparison.

for further simulations. This especially, holds for detectors where a major fraction of the incident radiation is transmitted through the conversion layer.

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