Low-dose computed tomography of the abdomen and lumbar spine
This dissertation is dedicated to my parents and my family for their endless love, support, and encouragement.
Low-dose computed tomography of the abdomen and lumbar spine
Abstract


Radiography is a common radiologic investigation despite abundant evidence of its limited diagnostic value. On the other hand, computed tomography (CT) has a high diagnostic value and is widely considered to be among the most important advances in medicine. However, CT exposes patients to a higher radiation dose and it might therefore not be acceptable simply to replace radiography with CT, despite the powerful diagnostic value of this technique. At the expense of reduced CT image quality, which could be adjusted to the diagnostic needs, low-dose CT of abdomen and lumbar spine can be performed at similar dose to radiography. The aim of the current thesis project was to evaluate low-dose CT of the abdomen and lumbar spine and to compare it with radiography. The hypothesis was that CT would give better image quality and diagnostic information compared to radiography at similar dose levels. Firstly, the diagnostic accuracy of low-dose CT of the abdomen was evaluated. Results showed that low-dose CT of abdomen has a high sensitivity and specificity compared to radiography, i.e., it has higher diagnostic accuracy. Similar results were obtained from our systematic review. Secondly, in a phantom study, an ovine phantom was scanned at various CT settings. The image quality was evaluated to obtain a protocol for the optimal settings for low-dose CT of lumbar spine at 1 mSv. This new protocol was then used in a clinical study to assess the image quality of low-dose CT of the lumbar spine and compare it to radiography. Results showed that low-dose CT has significantly better image quality than radiography. Finally, the impact of Iterative reconstruction (IR) on image quality of lumbar spine CT was tested. Iterative reconstruction is a recent CT technique aimed to reduce radiation dose and/or improve image quality. The results showed that the use of medium strength IR levels in the reconstruction of CT image improves image quality compared to filtered back projection. In conclusion, low-dose CT of the abdomen and lumbar spine, at about 1 mSv, has better image quality and gives diagnostic information compared to radiography at similar dose levels and it could therefore replace radiography.

Keywords: Tomography, X-Ray Computed; Radiography; Radiation Dosage; Abdomen; Spine; Lumbosacral Region; Regression Analysis.

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Abbreviations

AEC  automatic exposure control
AP   antero–posterior
BMI  Body mass index
CI   confidence interval
CNR  contrast–noise ratio
CT   computed tomography
CTDI_{vol} volume computed tomography dose index
DAP  dose area product
DISH diffuse idiopathic skeletal hyperostosis
DLP  dose length product
E    effective dose (an estimation of the relative biological risk)
ED   emergency department
EDLP region-specific conversion coefficient
EMI  Electric and Musical Industries
FBP  filtered back projection
FOV  field of view
GEE  Generalized Estimating Equation
HU   Hounsfield unit
ICRP International Commission on Radiological Protection
IR   iterative reconstruction
kV   kilovolt (tube potential)
mAs  milliampere–seconds (tube charge)
mGy  milligray
MPR  multiplanar reconstruction
MRI  magnetic resonance imaging
MSCT multislice computed tomography
mSv  millisievert
NPV  negative predictive value
OR   odds ratio
PACS picture archiving and communication system
PPV  positive predictive value
QUADAS-2 Quality Assessment of Diagnostic Accuracy Studies v.2
ROI  region of interest
RP   relative position
RV   rank variance
SAFIRE sinogram-affirmed iterative reconstruction
SD   standard deviation
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tr>
<td>SI</td>
<td>sacroiliac</td>
</tr>
<tr>
<td>SPSS</td>
<td>Statistical Package for the Social Sciences</td>
</tr>
<tr>
<td>VGR</td>
<td>visual grading regression</td>
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Introduction

On November 8th, 1895, X-rays were discovered by Wilhelm Conrad Röntgen, Professor of Physics and head of the Department of Physics at the Julius-Maximilian University in Würzburg, Germany. He observed that when a current of cathode rays passed across an evacuated glass bulb, a barium platinocyanide screen fluoresced. He realized the significance of this observation at once. Simultaneously he noted the effect of the new phenomenon on photographic plates, that by recording the X-rays on a photographic plate, an image could be created. On December 28th, 1895, his manuscript “Über eine neue Art von Strahlen” (On a New Kind of Rays), describing the characteristics of X-rays, was submitted to the Würzburg Physical Medical Institute. The radiographs were initially made onto glass photographic plates that were coated with emulsion on one side and had to be placed into light tight cassettes or envelopes. Röntgen’s discovery enables us to see through the body. This was demonstrated in scientific and medical meetings at the time, and filled the headlines. The early version of the X-ray tube was modified in 1896 by Henry Jackson who developed the focus tube, a cup-shaped cathode that focuses the cathode rays onto the platinum anode target and changes their energy into invisible X-rays when the cathode rays hit the anode. The tube resulted in a considerable improvement in image quality. The device has been used in the medical field since 1896 and the first X-ray examination in Sweden was performed that year. X-rays are considered as one of the major medical discoveries and Röntgen was awarded the first Nobel Prize in Physics in 1901.

At the turn of the century, there were ten X-ray machines in Sweden. One of the pioneers of the X-ray in Sweden was Gösta Forssell (1876–1950), the first professor in radiology in the world. Forssell was also the first scientist to realize that cancer patients could be treated with X-rays. In 1900, the American Roentgen Ray Society was founded. Film was introduced by Eastman in 1918. However, the image quality on glass photographic plate was excellent and it took some time for film to replace it.

The absence of protection around the early X-ray tubes resulted in considerable injury to the operators. The problem was compounded by the common practice of operators of looking at their own hand with a fluorescent screen to test the apparatus. It took some time to realize that it was
the X-rays themselves that were causing the injuries. Many of the early pioneers who worked with X-rays had cancer induced by the Roentgen rays. Another lethal risk was the practice of having uninsulated electric wires delivering electricity to the X-ray apparatus, with the risk of electrocution. Standards for exposure and protection were gradually introduced.

**Radiography**

Abdominal radiography is often used as urgent initial investigation in acute, non-traumatic abdominal pain, mainly to check for bowel obstructions or bowel perforation. However, there is a wide variety of underlying causes and presentations of non-traumatic abdominal pain, with a broad spectrum of complications, which may vary from life-threatening diseases requiring emergency surgery to mild, self-limiting causes. Thus, patients with abdominal pain often have vague symptoms and may have a variety of diagnoses other than bowel obstructions and bowel perforation. Furthermore, abdominal pain is the most common reason for a visit to the emergency department (ED), accounting for 8 million (7%) of the 119 million ED visits in the USA in 2006. Several studies have demonstrated that abdominal radiography has limited value in the evaluation of acute abdominal pain and yields a high percentage of normal or non-specific findings. Whether abdominal radiography contributes to therapeutic decision making remains questionable, particularly in the case of a negative result. This raises questions about the value of such investigation.

Lumbar spine radiography has been used as the initial radiological examination for acute or chronic back pain. It is usually performed to find injuries or diseases that affect the lumbar spine area. These problems may include spinal fractures, infections, dislocations, or tumors. Radiography is also used to evaluate scoliosis or in the case of spinal defects. In the context of trauma, radiography has been widely used for imaging of the lumbar spine. Radiography is usually performed to demonstrate the anatomy and appearance of injuries to that area, but it does not highlight abnormal or specific findings. The diagnostic value of lumbar spine radiography is limited, partly because of obscuring superimposed structures, such as abdominal contents and gastrointestinal gas. Incorrect management of patients with spinal injury may lead to, or exacerbate, neurological deficit. The clinical and radiological assessment of suspected lumbar
spine injuries therefore depends on careful consideration of both the clinical and the radiological findings.

Despite abundant evidence of the limited value of conventional abdominal and lumbar spine radiography, radiographic studies are still the most common initial radiologic investigation in both acute and chronic cases. Many physicians rely on abdominal and lumbar spine radiography as a simple and widely available preliminary diagnostic modality with relatively low radiation, the effective dose being about 1 milliSievert (mSv), despite the fact that radiographs often give unclear information, making them unsuitable for detecting most diagnoses.

**Computed tomography**

The invention of the CT scanner is considered as one of the most important advances in medicine. It was a successful result of advanced and continuous research across many disciplines in radiology, medicine, science, and engineering. The story begins with the construction of the Electric and Musical Industries (EMI) scanner which was described by Godfrey Hounsfield firstly in 1973. However, already in 1964 Allan McLeod Cormack from South Africa had published a mathematical model on how to detect attenuation differences in a body. His results received very little interest, and Hounsfield was completely unaware of them when designing his invention. They shared the Nobel prize in Physiology or Medicine 1979. In 1980, a new generation of CT scanners appeared and through the 1980s, CT scanners with “step-and-shoot” mode were developed. The CT scanner had a stationary table and a rotating X-ray beam and detector set. Spiral (or helical) CT appeared in 1990, which was a major advance on earlier CT scanners. The spiral scanner was able to scan the entirety of the chest or abdomen in a single breath hold. The next important breakthrough came in 1998 with the four-detector row CT scanner (multidetector CT), which was improved to a 16-detector row CT scanner in 2002 and a 64-detector row CT scanner in 2004. In 2006, the dual-energy CT scanner was introduced, which was capable of improving the imaging, e.g., of coronary arteries. In 2010, a 16 cm-wide, 320-row detector with 640-slice reconstruction was introduced, making it possible to capture an entire organ at one time, e.g., the entire heart can be captured in just one non-helical scan over a single heartbeat.
Computed tomography has revolutionized diagnostics in healthcare because of its high diagnostic value. Integrating CT into routine care has improved patient health care dramatically.

Computed tomography (CT) has had a profound effect on the practice of medicine. Both the spectrum of clinical applications and the role that CT has played in enhancing the depth of our understanding of disease have been profound. Although almost 90000 articles on CT have been published in peer-reviewed journals over the past 40 years, fewer than 5% of these have been published in Radiology. Nevertheless, these almost 4000 articles have provided a basis for many important medical advances. By enabling a deepened understanding of anatomy, physiology, and pathology, CT has facilitated key advances in the detection and management of disease.

Today, CT is considered as one of the most important non-invasive imaging tools, especially using oral and intravenous contrast media, for the diagnostic workup of acute abdominal pain and to answer clinical questions. There is much scientific evidence supporting that CT is a powerful diagnostic modality to detect most of the underlying causes of acute abdominal pain, with the exception of acute cholecystitis, predominantly in diverticulitis, bowel obstruction, bowel ischemia, appendicitis, and renal colic. Computed tomography has the potential to positively affect the outcome of patients with acute abdomen, as an accurate diagnostic assessment is critical to identify patients in need of urgent surgical intervention. There are many advantages of CT in musculoskeletal radiology. Computed tomography is superior to radiography for detection of acute cervical spine injury and craniomaxillofacial injuries in trauma patients and it has been reported that CT reduces the risk of missing a fracture of the thoracolumbar spine. Spiral CT with 3D reconstructions provides quick and important information in assessing complex fractures with an accurate demonstration of different types of fractures and, thus, enables more accurate preoperative surgical planning. Moreover, CT is more sensitive, compared to radiography, for evaluation of multiple myeloma.

Using conventional settings, CT delivers much higher radiation doses than radiography; as mentioned previously, the effective dose for radiography of the abdomen or lumbar spine is about 1 mSv. The effective dose of a “standard” abdominal CT is about 10–15 mSv and the effective dose of CT of the lumbar spine is about 9 mSv, but doses can be as high as 19 mSv. Advances in CT diagnostics, such as spiral scanning tech-
niques, and the development of multi-detector row CT technology, have led to a dramatic increase in the number of CT examinations globally and, therefore, have led to an increase in the collective radiation dose\textsuperscript{19, 22, 23}. The total number of CT examinations performed annually in the USA has risen from approximately 3 million in 1980 to nearly 70 million in 2007\textsuperscript{19, 22}, representing a more than 20-fold increase. Statistics from the UK indicate a twelvefold increase in CT use over the past two decades\textsuperscript{23}.

Consequently, patients are exposed to higher levels of radiation by using CT compared to conventional radiography. The biological impact of diagnostic imaging exposure is based on the linear no-threshold model, i.e., the risk of cancer induction is estimated to increase proportionally to organ dose\textsuperscript{19, 22, 24–27}. Because of this, awareness has been raised of the hazards of medical ionizing radiation and the need to reduce it as much as possible\textsuperscript{28}. It might therefore not be acceptable simply to replace radiography with standard (full dose) CT, despite the anticipated higher diagnostic yield, due to the much higher radiation exposure associated with standard CT in comparison to conventional radiography.

**Low-dose computed tomography**

It is possible to perform CT at a much lower radiation dose than standard CT, at the expense of increased noise and reduced image quality. The radiation dose can even be adjusted to the same relatively low dose as used for abdominal or lumbar spine radiography\textsuperscript{22, 28}. Low-dose CT can be considered as an intermediate between conventional radiography and standard-dose CT, but yields a lower image quality compared to standard-dose CT. Therefore, using reduced-dose CT does not necessarily imply increased radiation exposure compared to radiography, providing an image quality that is consistently adjusted to the diagnostic needs.

The CT protocols used for standard-dose CT examinations are not immediately suitable for low-dose examinations, and different settings enable adjustment to obtain optimal image quality with the lower dosage used. There are several different settings and techniques that can affect the radiation dose in CT.

In the current thesis, some of the following settings were adjusted and techniques applied in low-dose CT to improve image quality and reduce the radiation dose:
• Tube potential (in kilovolt (kV)), which indicates the penetration power of the X-ray beam. Using a higher kV results in increasing the radiation dose, if all other technical parameters are held constant.

• The tube charge (mAs), which determines the intensity of the primary beam. It is directly proportional to the radiation dose and effective dose if all other technical parameters are held constant.

• Automatic exposure control (AEC), a CT technique that adapts the radiation dose to the size and shape of the patient by automatically modulating the tube current to compensate for variations in patient attenuation, both between different patients and within any given patient.

• The convolution filter (kernel or reconstruction algorithm), which is a mathematical filter function during image reconstruction of CT images. There are various types of convolution filters, sharp to smooth, which can be selected according to the tissue characteristics.

• Iterative reconstruction (IR), a recent technique that can be used instead of the standard convolution filter, filtered back projection (FBP), to reduce radiation dose and/or improve image quality.

Computed tomography of the abdomen or lumbar spine at this low dose level, as used for radiography, may have a higher diagnostic value compared to radiography and may give more information on anatomy as well as on pathologic changes.
Aims

Overall aim
The aim of the current thesis was to evaluate low-dose CT of the abdomen and lumbar spine and compare it to corresponding radiography, using a comparable radiation dose, of around 1 mSv. The hypothesis was that CT would give better image quality and diagnostic information compared to radiography at similar dose levels.

Specific aim of each paper
Paper 1: To evaluate the diagnostic accuracy of low-dose CT compared to abdominal radiography in the investigation of acute abdominal pain. A second aim was to perform a systematic literature review to evaluate previous studies.

Paper 2: To optimize the settings for lumbar spine CT with the same effective dose as used for lumbar spine radiography, i.e., around 1 mSv, by using an ovine model.

Paper 3: To evaluate and compare image quality and anatomic and diagnostic information from low-dose CT of the lumbar spine to lumbar spine radiography.

Paper 4: To evaluate the image quality of low-dose CT of the lumbar spine with IR, compared to conventional FBP reconstruction.
Material and methods

Paper 1: Diagnostic accuracy of low-dose CT compared with abdominal radiography in non-traumatic acute abdominal pain: Prospective study and systematic review

Patients
During 3 months, a convenience sample of 58 patients with acute non-traumatic abdominal pain, referred for abdominal radiography, were included in the study. Informed consent was obtained. There were 30 male and 28 female patients, mean age 65 years, range 21–97 years. They were referred from different departments, mainly from the ED (42 patients). Inclusion criteria were: adult patients with non-traumatic, acute abdominal pain who were referred for radiography. Exclusion criteria were: age below 18 years, pregnancy, coma, dementia, or inability to understand instructions. The study was approved by the regional ethics board.

Imaging techniques
Abdominal radiography was immediately followed by low-dose CT, performed with settings providing approximately the same effective dose as radiography. Abdominal radiography was performed with two anteroposterior (AP) images (upper and lower abdomen) in the supine position using a flat panel detector (DigitalDiagnost, Philips Medical Systems, Best, The Netherlands) at 70 kV with AEC. Furthermore, a left lateral decubitus view was obtained with a horizontal X-ray beam using storage phosphor plates (AC-3, Philips Medical Systems, Best, The Netherlands). Tube potential was 70 kV and the tube charge 100 mAs. Radiography therefore consisted of a minimum of three exposures; extra images could be taken if needed.

Low-dose CT was performed using a Brilliance CT (Philips Medical Systems, Best, The Netherlands) (53 studies) or an Mx8000 (Philips Medical Systems, Best, The Netherlands) scanner (five studies). All examinations were made without oral or intravenous contrast media. The scanogram was performed at 90 kV and 30 mA from about 10 cm above the diaphragm to the pelvic floor. Axial scanning was performed supine from about 5 cm above the diaphragm to the pelvic floor, making it possible to also evaluate the base of the lungs. Imaging parameters for both scanners
were: 120 kV using 20 mAs/slice; rotation time, 0.75 s; field of view (FOV), 420x420 mm; reconstruction thickness, 5 mm; no overlap. With the Brilliance scanner, the imaging parameters further included: collimation, 6 x 3 mm; pitch, 1.213. With the Mx8000 scanner, the imaging parameters further included: collimation, 4 x 2.5 mm; pitch, 1.25.

**Dose calculations**
For abdominal radiography, the tube charge was recorded for each projection. The effective dose was calculated with the computer program PCXMC 2.0 (Finnish Radiation and Nuclear Safety Authority, Helsinki, Finland) using clinical settings and the average tube charge, including retakes, for each projection. For low-dose CT, the calculations were done with the software CT-Expo v 2.3 (SASCRAD, Buchholz, Germany) and settings were as for the Brilliance CT scanner. The conversion factors from the International Commission on Radiological Protection (ICRP) recommendations (ICRP 103) were used to calculate the effective dose.  

**Image interpretation**
For the image review, abdominal radiography consisting of at least three exposures, and low-dose CT consisting of the CT scanogram and 5 mm thick axial slices were used. All images were interpreted independently and in random order by three radiologists with at least 15 years’ experience in abdominal radiography. The reviewers were blinded to all patient data and specific medical histories and, furthermore, to all results of physical examinations, laboratory tests, and other imaging. Each reviewer had a list of common possible diagnoses to be evaluated. Image reviews were made at a workstation with a picture archiving and communication system (PACS) and a color monitor (MultiSync LCD1880SX, NEC, Tokyo, Japan). No post-processing except zooming and alteration of the gray scale was used.

**Reference standard**
The reference standard used was the final clinical diagnosis as determined by a consultant surgeon, using all medical history, clinical examinations, additional radiological studies and surgical details, and a 5 year follow-up period. The following classification was used:
• Positive: Patients with acute abdominal pain that required medical or surgical management or treatment to improve their condition were considered positive.

• Negative: Self-limiting causes: Patients with unspecific abdominal pain that did not require treatment or management, except analgesics, to improve their condition were considered negative, i.e., unspecific abdominal pain that resolved spontaneously, with a negative 5 year follow-up period.

Classification of the index test results:

• True positive: The test (low-dose CT or abdominal radiography) explained the abdominal pain in a positive case.

• True negative: The test gave no finding to explain the acute abdominal pain in a negative case, i.e., a correct negative finding.

• False positive: The test gave incorrect or false findings in a negative case.

• False negative: The test gave no finding to explain the abdominal pain in a positive case, i.e., a missed diagnosis.

Systematic review
A literature search was performed on September 2nd, 2014, in the database PubMed/MEDLINE with the search expression (tomography, X-ray computed) AND “Abdomen, Acute/radiography” [MeSH]. The sole inclusion criterion was abdominal radiography and low-dose CT performed in a patient with non-traumatic abdominal pain. Exclusion criteria were: (a) Articles on another subject; (b) reviews, editorials, comments, or abstracts; (c) case reports; (d) studies including only patients with flank pain associated with urinary stone disease; (e) insufficient data to calculate sensitivity and specificity at the patient level; (f) duplicate publications; (g) articles not in English, German, French, or a Scandinavian language. The reference test was required to allow calculation of sensitivity and specificity at the patient level. Two reviewers independently read all titles and abstracts. All articles that were considered worth including by at least one reviewer were selected for reading in full text. After independent reading of full texts, articles fulfilling the inclusion criteria were selected. Disagreements were resolved in consensus. For each included study, patient characteristics and radiation dose level were noted. The numbers of true positive,
false positive, false negative, and true negative results were recorded. Where only sensitivity and specificity were reported, these numbers were imputed.

All included studies were assessed for methodological quality by two independent reviewers, according to the Quality Assessment of Diagnostic Accuracy Studies version 2 (QUADAS-2) \(^{31}\). Disagreements were resolved in consensus.

**Statistics**

Sensitivity, specificity, positive and negative predictive values, and likelihood ratios were calculated for each test from pooled data of all observations (n=174; 58 cases x three observers). Interobserver agreement for all reviewers for each method was estimated by unweighted kappa analysis (Cohen's kappa) for three observer pairs (R1 and R2, R1 and R3, and R2 and R3) using IBM SPSS Statistics for Windows version 22 (IBM Corp., Armonk, NY, USA). In the systematic review, the large heterogeneity of the included articles prohibited a meta-analysis, and a descriptive analysis was performed instead.
Paper 2: Low-dose computed tomography of the lumbar spine: A phantom study on imaging parameters and image quality

A phantom was scanned repeatedly using different settings to determine the optimal setting for the highest diagnostic image quality.

Phantom
The phantom consisted of an ovine lower thoracic and lumbar spine (from the lowest two thoracic vertebra to the caudal border of the sacroiliac (SI) joints), with all soft tissues around the vertebrae preserved except the skin. It was placed in a 20 liter plastic container filled with water. The container was 49 cm long, 28 cm wide, and 22 cm deep, with a circumference of 97 cm. The cross-sectional area of the phantom, a rectangle with rounded corners, was 608 cm². The imaged phantom therefore consisted of water, the vertebral column, and muscle and connective tissue around the spine.

Computed tomography techniques
The phantom was imaged with a Somatom Definition AS scanner (Siemens, Erlangen, Germany) (40 channels) using different tube potentials (kV), reference tube charges (reference mAs), and convolution filters (soft to hard). The reference mAs is the manufacturer’s expression of the effective mAs used for a “reference patient” weighing 70–80 kg. For smaller patients, the effective mAs is consequently lower, and for larger patients higher, than the reference mAs. Imaging was done from the middle of the next lowest thoracic vertebra to the caudal border of the SI joints with a sector collimation of 40 x 0.625 mm, rotation time 0.5 s, tube potential set at 80, 100, and 120 kV, and reference mAs from 330 to 10 mAs, and using AEC. Scan length was 27 cm, which is the approximate scan length between Th 11 and S 2 in the human body. For every scan, the volume CT dose index (CTDIvol in milligray (mGy)) and dose length product (DLP: the product of CTDIvol and scan length in mGy*cm) were recorded. The effective dose (E: the estimation of the relative biological risk) was calculated as E = DLP*EDLP. The EDLP is a region-specific conversion coefficient; for the lumbar spine is 0.017 mSv/mGy*cm³. The phantom was initially imaged according to the standard clinical CT protocol for the lumbar spine at our institution and again with different tube potential and progressively lower reference mAs settings (Table 1). All scans with an effective dose >1 mSv were excluded from further evaluation.
**Table 1** Settings and effective dose for computed tomography (CT) scans performed with different tube potentials and reference milliampere–seconds (mAs).

<table>
<thead>
<tr>
<th>Scan</th>
<th>Tube potential (kV)</th>
<th>Reference mAs</th>
<th>Effective mAs</th>
<th>CTDI&lt;sub&gt;vol&lt;/sub&gt; (mGy)</th>
<th>Effective dose (mSv)</th>
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<tr>
<td>1</td>
<td>120</td>
<td>330</td>
<td>207</td>
<td>16.9</td>
<td>7.75</td>
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<td>120</td>
<td>165</td>
<td>105</td>
<td>8.57</td>
<td>3.93</td>
<td>&gt;1 mSv, excluded</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>82</td>
<td>51</td>
<td>4.22</td>
<td>1.94</td>
<td>&gt;1 mSv, excluded</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>40</td>
<td>25</td>
<td>2.04</td>
<td>0.94</td>
<td>Effective dose of 1 mSv</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>30</td>
<td>18</td>
<td>1.52</td>
<td>0.72</td>
<td>CTDI&lt;sub&gt;vol&lt;/sub&gt; 75% of scan 4</td>
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<td>12</td>
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<td>CTDI&lt;sub&gt;vol&lt;/sub&gt; 50% of scan 4</td>
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<tr>
<td>10</td>
<td>80</td>
<td>153</td>
<td>92</td>
<td>2.07</td>
<td>0.95</td>
<td>Effective dose of 1 mSv</td>
</tr>
<tr>
<td>11</td>
<td>80</td>
<td>77</td>
<td>44</td>
<td>1.00</td>
<td>0.46</td>
<td>CTDI&lt;sub&gt;vol&lt;/sub&gt; 50% of scan 10</td>
</tr>
</tbody>
</table>

Axial reconstructions of 3 mm thickness and 3 mm increment, and sagittal reconstructions of 2 mm thickness and 2 mm increment were performed. All images were archived in the local PACS.

**Image interpretation**

All images were evaluated by five radiologists blinded to the CT settings. Free use of all PACS tools was allowed at image review. For all combinations of settings, including tube potentials, reference mAs, and convolution filters, the image quality was assessed on axial multiplanar reconstruction (MPR) images from one predetermined transverse process to the next transverse process (the same for all scans), and on sagittal MPR images at the intervertebral joints between the lowest and second lowest lumbar vertebra.

Image quality was assessed according to a modification of the European Guidelines for Multislice Computed Tomography (MSCT) of 2004, quality criteria for lumbar spine CT<sup>18</sup>.

The following structures were assessed for image quality:

- Sharp reproduction of cortical bone
- Sharp reproduction of trabecular bone
• Sharp reproduction of the intervertebral joints
• Sharp reproduction of the intervertebral radicular canals

The scoring levels for each criterion were 0 = confident that the criterion is not fulfilled; 1 = somewhat confident that the criterion is not fulfilled; 2 = indecisive whether the criterion is fulfilled or not; 3 = somewhat confident that the criterion is fulfilled; and 4 = confident that the criterion is fulfilled. The total score for a CT scan consequently ranged from 0 to 160 (five reviewers x four scored structures x two imaging planes [axial and sagittal] x maximum score 4).

Furthermore, a visual comparison of the different scans was performed, where each reviewer ranked the scans from the highest to the lowest image quality for each scan series.

Image noise was measured by manually selecting 20 regions of interest (ROIs), 10 mm in diameter, in the water section of the phantom. Noise was calculated as the mean value of the standard deviation (SD) in Hounsfield units (HUs). Image contrast was measured as the average HU of bone. One 10 mm ROI was placed on the trabecular bone of the vertebral body in the same section as selected for the noise measurement. The contrast–noise ratio (CNR) was calculated as the ratio between contrast and noise. A subjective evaluation of the acceptability of image noise was done by all five reviewers for each scan.

Selection of tube potential
Computed tomography scans at three different tube potential levels (80, 100, and 120 kV) and two different CTDIvol levels, corresponding to an effective dose of 0.5 mSv and 1 mSv, were reconstructed with the same convolution filter, B41f (medium). Each scan was evaluated separately by all reviewers on separate occasions for each dose level, at least 2 days apart to minimize image recollection. Optimal tube potential, based on the image quality scores, visual comparison, and noise measurement, was determined to be 120 kV.

Computed tomography scans at three different tube potential levels (80, 100 and 120 kV) at two different CTDIvol levels, corresponding to an effective dose of 0.5 mSv and 1 mSv, were reconstructed with the same convolution filter, B41f (medium). Each scan was evaluated separately by all
reviewers on separate occasions for each dose level, at least 2 days apart to minimize image recollection. Optimal tube potential was determined to be 120 kV based on the image quality scores, visual comparison and noise measurement.

Selection of reference mAs and convolution filter
After determining the optimal tube potential, further assessment of image quality was done at different reference mAs levels (10, 20, 30, and 40 mAs), which all gave an effective dose of about 1 mSv or less (Fig. 1). Every scan was reconstructed with five different convolution filters (whose smoothness level, according to the scanner manual, is given in parentheses): B20f (smooth), B31f (medium smooth), B41f (medium), B50f (medium sharp), and B60f (sharp) (Fig. 2). Each reference mAs level was evaluated by the reviewers, who were blinded to the reference mAs and convolution filter, on four different occasions in random order.
Fig. 1 Phantom images with the convolution filter B41f (medium) at different reference mAs levels: (A) 10 mAs; (B) 20 mAs; (C) 30 mAs; and (D) 40 mAs.
Fig. 2 Phantom images at reference mAs 30 with different convolution filters: (A) B20f (smooth); (B) B31f (medium smooth); C) B41f (medium); (D) B50f (medium sharp); and (E) B60f (sharp).

**Statistical analysis**
The significance of differences between different tube potential settings for image noise and CNR was tested using the Mann-Whitney U test with a confidence level of 95%. The image quality data are ordinal. In the statistical evaluation of the results, we used the approach for paired ordinal data proposed by Svensson. The observations are linked to the pairs of observations, consisting of the image with the new CT setting, tube potential, and convolution filter, compared to the reference. The systematic change in position for the group with a new setting and the group with the reference setting is described by the empirical measure relative position (RP). Relative position can have a value between −1 and 1; a positive RP value indicates a change towards higher scores, i.e., the group with the new setting is better than the reference, and vice versa. The statistical variable that was used as a measure of individual change was the relative rank variance (RV). The closer the RV is to 0, the more homogenous the measurable change is for the group.
Paper 3: Low-dose CT of the lumbar spine compared with radiography: A study on image quality with implications for clinical practice.

Patients
The inclusion criterion for this study, which was approved by the regional ethics committee, was adults referred for lumbar spine radiography. Exclusion criteria were age below 18 years, pregnancy, coma, dementia, or inability to understand oral or written instructions. A power analysis showed that, with better image quality compared to the reference method in 70% of the cases, 51 cases would be needed for 80% power. In a convenience sample, 51 patients (16 men, 35 women) gave informed consent and agreed to participate (53 were invited, two declined to participate). Most patients were referred from primary health care (n=48), two were referred from the orthopedic department, and one from the neurological department. The major primary indication was low back pain without known, serious underlying conditions (48 cases with back pain, ten with neurological symptoms, 38 without; one with paraesthesia in the thigh, another referred for control of osteosynthesis, and one for vertebral compression fracture).

Patients’ mean age was 58 years (SD 13.9, range 21–81 years). Mean weight was 79.6 kg (SD 15.6, range 55–125 kg) and height 169 cm (SD 9.3, range 152–194 cm). Mean body mass index (BMI) was 27.7 (SD 4.0, range 20–38). There were no underweight subjects. The patients were classified as being of normal weight (BMI 18.5–24.9), overweight (BMI 25.0–29.9), or obese (BMI >30.0).

Imaging techniques
Lumbar spine radiography and low-dose CT were performed on the same day. Radiography was performed on a digital X-ray system (DRX-Evolution, Carestream Health, Rochester, NY, USA) with a flat panel detector (PaxScan Csl, Varian Medical Systems, Salt Lake City, UT, USA), pixel spacing 0.139 mm x 0.139 mm, image depth 12 bits. Standard clinical settings for lumbar spine were used: 75 kV for the AP projection, and 85 kV for the lateral and lumbosacral joint projections using AEC. The average number of exposures was 3.5 (range 2–5) due to clinical status, imaging requirements, and retakes.
Low-dose CT was performed using a Somatom Definition AS scanner with 40 channels (Siemens, Erlangen, Germany), using settings from a phantom study \(^{34}\), giving about 1 mSv effective dose; tube potential 120 kV, reference mAs 30, collimation 40 x 0.6 mm, rotation time 0.5 s, pitch 1.4, FOV 200 x 200 mm, convolution filter B41f (medium plus), with automatic dose modulation. Axial, coronal, and sagittal reconstructions, i.e., MPRs, with 2 mm thickness and 2 mm increment, were sent to the PACS.

**Image interpretation**

The 102 examinations (51 from each modality) were presented to reviewers in random order. Five reviewers, with 8, 10, 12, 25, and 32 years’ experience in diagnostic radiology, independently scored all studies blinded to patient data and using the PACS with free use of the PACS tools.

Scoring of image quality was according to a modification of the European Guidelines on Quality Criteria for CT (EUR 16262) \(^{18}\) and Diagnostic Radiographic Images (EUR 16260) \(^{35}\). Each reviewer rated the following criteria using a scale of 0–4:

- Sharp reproduction of the disc profile and the upper and lower plate surfaces of vertebrae
- Sharp reproduction of the cortical (cortex) and the trabecular bone
- Sharp reproduction of the intervertebral foramina and pedicles
- Sharp reproduction of the intervertebral joints
- Sharp reproduction of the spinous and transverse processes
- Reproduction of the adjacent soft tissues
- Sharp reproduction of the SI joints (the part of the joints included in the examination)
- Absence of any obscuring, superimposed abdominal contents, or gastrointestinal gas

The scoring levels for each criterion were: 0 = confident that the criterion is not fulfilled; 1 = somewhat confident that the criterion is not fulfilled; 2 = indecisive about whether the criterion is fulfilled or not; 3 = somewhat confident that the criterion is fulfilled; and 4 = confident that the criterion is fulfilled. Time needed to review each case was recorded by all reviewers. One reviewer scored all examinations again 6 months later to assess intraobserver agreement.
Assessment of pathology: Three common radiological findings (disc degeneration, intervertebral joint osteoarthritis, and spondylosis/diffuse idiopathic skeletal hyperostosis (DISH)) were evaluated. For each detected type of pathology, the vertebral level(s) was noted. Reviewers also scored on a 3 point scale how clearly the lesions were seen and how certain the diagnosis was.

**Dose calculations**

For radiography, the dose area product (DAP) was measured for each projection using a DAP meter integrated in the equipment. The computer program PCXMC 2.0 (Finnish Radiation and Nuclear Safety Authority, Helsinki, Finland) was used to calculate the effective dose for each BMI category with the average DAP of each projection. The field size at the detector was $18\times42$ cm for the AP and lateral projections and $18\times30$ cm for the lumbosacral projection.

For CT, the effective mAs was recorded for each examination and the average value used to calculate the effective dose for each BMI category with the software CT-Expo 2.3 (SASCRAD, Buchholz, Germany). The scan area covered Th 12 to S 2 in a virtual phantom.

**Statistical analysis**

In studies such as the present, well-defined criteria, such as the EU criteria, are often used, and the results are scored using a scale with a limited number of points. In statistical terms, the score is defined on an ordinal scale, and this requires adapted statistical methods. In this study, the data for each image quality criterion were analyzed using the Generalized Estimating Equation (GEE) model because of repeated measurements as each patient was assessed by five observers for each method. This kind of model is a form of logistic regression for repeated measurements with ordinal scaled outcome variables and is also called proportional odds model for repeated measurements. Odds ratios (ORs) with 95% confidence intervals (CIs) were used for the measurement of associations. An OR of 1 is interpreted as indicating no difference between methods; an OR >1 is interpreted as meaning that low-dose CT is a better method compared to radiography. All statistical analyses were performed using SPSS version 22 (IBM Corp., Armonk, NY, USA). The same analysis was performed after stratifying data into BMI subgroups.
Interobserver agreement for all five reviewers using free-marginal multirater kappa ($\kappa_{\text{free}}$) was estimated\textsuperscript{37}. The scoring scale was converted from a 5 pint to a 3 point scale (where 1 = the criterion is not fulfilled; 2 = indecisive; and 3 = the criterion is fulfilled). Data from the first and second observation of one reviewer was used to evaluate intraobserver agreement. Calculations were performed with an online kappa calculator\textsuperscript{38}. Values of free-marginal kappa can range from -1.0 to 1.0, with -1.0 indicating perfect disagreement worse than chance, 0.0 indicating agreement equal to chance, and 1.0 indicating perfect agreement. A rule of thumb is that a kappa of 0.70 or above indicates adequate agreement.
Paper 4: Impact of iterative reconstruction on image quality of low-dose CT of the lumbar spine.

Patients
Patients who were referred for low-dose CT of the abdomen were invited to participate in the study. A power analysis indicated that if about 70% of cases had IR image quality better than the reference (FBP), 51 patients would be required to achieve 80% power. The estimation was that 55 patients needed to be included to compensate for dropouts. Exclusion criteria were: coma, dementia, age under 18 years, and inability to understand oral or written study information. The study was approved by the regional ethics board. A convenience sample was collected during a period of 5 weeks. In total, 58 patients were asked to participate and three of them declined. Altogether 55 patients (22 male and 33 female) participated in the study. Mean age was 60 years (SD 21.2, range 20–94 years).

Computed tomography technique
The study was performed on a 2 x 128 channel Somatom Definition Flash CT scanner (Siemens, Erlangen, Germany). Based on settings used in a previous clinical study, the CT settings were: tube voltage, 120 kV; reference mAs, 30; collimation, 128 x 0.6 mm, and automatic dose-modulation.

Image reconstruction
From raw CT data acquired for low-dose clinical abdominal CT, lumbar spine CT images were reconstructed for the current study. Therefore, patients were not subjected to any additional imaging or radiation. The reconstructions of lumbar spine images were performed with a medium filter (B41f) using FBP and four different levels of IR, sinogram affirmed iterative reconstruction (SAFIRE), the Siemens proprietary IR algorithm. Four levels of SAFIRE, IR2 (I41f 2), IR3 (I41f 3), IR4 (I41f 4) and IR5 (I41f 5), ranging from low to high noise reduction, were evaluated. The reconstructions were obtained in the axial and sagittal planes with 2 mm slice thickness and 2 mm increment. The lowest IR level (IR1) was excluded as it has a minimal effect on image quality compared to FBP. The settings were designed to deliver an effective dose of about 1 mSv as in previous phantom and clinical studies at our institution.
**Image quality assessment**

All images were stored and reviewed in a PACS. Five radiologists, with 9, 12, 13, 25, and 30 years’ experience, respectively, reviewed the images, blinded to patient and image information.

In a first step, a randomized list of 275 CT reconstructions (axial and sagittal images), 55 patients by five reconstruction algorithms, was reviewed. All reviewers performed a visual grading for each reconstruction according to a modification of the European Guidelines on Quality Criteria for CT (EUR 16262) 18:

- Criterion 1: Sharp reproduction of cortical bone in the L3 vertebral body
- Criterion 2: Sharp reproduction of trabecular bone in the L3 vertebral body
- Criterion 3: Sharp reproduction of the intervertebral joints at the L3–L4 level on both sides
- Criterion 4: Sharp reproduction of the intervertebral radicular canals at the L3–L4 level on both sides
- Criterion 5: Sharp reproduction of the intervertebral disk profile at the L3–L4 level
- Criterion 6: Reproduction of the paravertebral muscles (intermuscular interface) at the L3–L4 level on both sides
- Criterion 7: Acceptable noise level at the L3–L4 level

The reviewers scored each criterion as 0 = confident that the criterion is not fulfilled; 1 = somewhat confident that the criterion is not fulfilled; 2 = indecisive about whether the criterion is fulfilled or not; 3 = somewhat confident that the criterion is fulfilled; or 4 = confident that the criterion is fulfilled.

In a second step, side-by-side visual grading of all image reconstructions was performed as a direct comparison of all images of each patient. Each reviewer ranked the five reconstructions (FBP and IR 2–5) from worst to best.

**Dose and noise estimation**

The CTDIvol for each patient was recorded. To estimate the noise, imaging of a Catphan phantom (The Phantom Laboratory, Salem, NY, USA) was
performed with the same settings as for the clinical patients in the study. Images were reconstructed with FBP and IR2–5 and image noise was calculated as the average of ten manually selected ROIs in the uniformity module of the phantom.

**Statistical analysis**
Visual grading regression (VGR) \(^{40}\), which is an ordinal logistic regression or proportional odds model, was used to compare the outcome image quality between different filter types. The outcome categories were combined as 0 = confident or somewhat confident that the criterion is not fulfilled; 1 = indecisive; and 2 = confident or somewhat confident that the criterion is fulfilled. Explanatory variables were filter type (using FBP filter as reference), reviewer, patient image, and image criteria. The regression was performed for all image criteria together, as well as for specific criteria, and also stratified by reviewer, the latter in order to examine the reviewer variability on image quality between different filter types. Ordinal regression was used to calculate ORs with 95% CIs as the measure of association. An OR of 1 was interpreted as no difference of image quality between filter types; an OR >1 was interpreted as meaning that the IR was rated better than FBP. If the 95% CI did not contain the value of 1.0, the association was statistically significant. All statistical analyses were performed using SPSS Statistics for Windows, version 22 (IBM Corp., Armonk, NY, USA).
Results

Paper 1: Diagnostic accuracy of low-dose CT compared with abdominal radiography in non-traumatic acute abdominal pain: Prospective study and systematic review

Diagnostic accuracy
Abdominal radiography had a sensitivity of 46% (95% CI limits 37–56%), a specificity of 87% (77–94%), a positive predictive value (PPV) of 86% (75–94%), and a negative predictive value (NPV) of 48% (38–57%). Low-dose CT had a sensitivity of 75% (66–83%), a specificity of 87% (77–94%), a PPV of 91% (83–96%), and an NPV of 66% (55–76%).

In 58 cases with acute non-traumatic abdominal pain, 37 positive cases required treatment excluding analgesics. There were 21 negative cases with non-specific abdominal pain (not requiring treatment, i.e., the pain resolved spontaneously).

Of the 37 positive cases, 16 (43%) were missed by all three reviewers on abdominal radiography, while only five cases (14%) were missed by all reviewers on low-dose CT scans (Table 2). Eight patients were diagnosed with bowel obstruction, and all were operated. All were detected by both methods. In one patient with incarcerated inguinal hernia (Fig. 3a) and in another with distal bowel obstruction due to a sigmoid cancer, the cause of the obstruction was identified with low-dose CT (Fig. 3b), but not with abdominal radiography. Another patient with sigmoid volvulus was identified with both methods by all observers. An incarcerated abdominal wall hernia in one patient was spotted by two observers on low-dose CT, but not on abdominal radiography. There were no signs of bowel obstruction on either abdominal radiography or low-dose CT in this patient. Four patients were diagnosed with diverticulitis and three of them were correctly detected by two observers on CT (Fig. 3c), but the fourth case, which was clinically considered to be diverticulitis, was identified by only one observer on low-dose CT. All four cases of diverticulitis were missed by abdominal radiography.
Table 2 Total number of all possible positive observations (n=111, based on all 37 positive cases x three observers), compared to the number of findings actually detected on low-dose computed tomography (CT) versus abdominal radiography.

<table>
<thead>
<tr>
<th>Final diagnosis</th>
<th>Total number of possible positive observations</th>
<th>Detected by low-dose CT</th>
<th>Detected by abdominal radiography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bowel obstruction</td>
<td>24</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Strangulated abdominal wall hernia without bowel obstruction</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Partial bowel obstruction</td>
<td>24</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>Gastroenteritis</td>
<td>6</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Colitis</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Diverticulitis</td>
<td>12</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Appendicitis (atypical location)</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Constipation</td>
<td>9</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Pancreatitis</td>
<td>6</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Internal hernia</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Urinary retention and hydronephrosis</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Ascites</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Abdominal hematoma due to pelvic fracture</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Pulmonary edema with pleural effusion</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Pneumonia</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Pneumonia with suspected diverticulitis</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>111</td>
<td>81</td>
<td>52</td>
</tr>
</tbody>
</table>
In one patient with acute pancreatitis, which was missed by abdominal radiography, all observers detected the disease on low-dose CT (Fig. 3d). Laboratory data and the clinical picture were consistent with pancreatitis. Follow-up with full-dose CT, 2 days later, showed mild progression of the pancreatitis. Two patients had bacterial enteritis, verified by bacterial cultures. One was detected by all observers on low-dose CT, whereas the other was detected by one observer on low-dose CT. Both cases were missed by all observers on abdominal radiography. One case with known prostate cancer had acute abdominal pain with vomiting which was due to development of urinary retention and bilateral hydronephrosis. The radiograph showed normal findings whereas low-dose CT showed urinary retention and bilateral hydronephrosis, identified by two observers. A case of ascites was detected by two observers on low-dose CT, but not on radiography. An abdominal hematoma due to a recent pelvic fracture was also missed on the abdominal radiograph.

Regarding interobserver agreement, the kappa value for the three observer pairs R1/R2, R1/R3, and R2/R3 was 0.7 (95% CI 0.5–0.9), 0.6 (0.4–0.8), and 0.5 (0.2–0.7), respectively, for abdominal radiography, compared to 0.8 (0.6–1.0), 0.5 (0.3–0.8), and 0.7 (0.5–0.9) for low-dose CT, a moderate to substantial agreement.

**Dose calculations**

For abdominal radiography, the average tube charge was 43 mAs and 41 mAs for the lower and upper abdominal projections and 103 mAs for the horizontal projection, resulting in an effective dose of 1.0 mSv including retakes. The calculations for low-dose CT resulted in a CTDIvol of 1.4 mGy and an effective dose of 1.2 mSv, including the scanogram that was estimated to be 0.1 mSv. Conversion factors from ICRP publication 103 were used in the calculations.
Fig. 3 Four examples of low-dose computed tomography (CT) findings in cases with acute non-traumatic abdominal pain: (a) An 86-year-old woman with intestinal obstruction due to an inguinal hernia; (b) an 80-year-old man with intestinal obstruction due to sigmoidal cancer; (c) a 91-year-old man with acute diverticulitis; and (d) a 46-year-old man with severe epigastric pain due to acute pancreatitis.
**Systematic literature review**

The literature search in PubMed/MEDLINE resulted in 302 hits. One more article was added from reference lists. Thirty-five articles were selected for reading in full text. Five of these fulfilled the inclusion and exclusion criteria and were selected for final analysis together with the results from the current study (Fig. 4). One of them was later excluded from the numerical analysis because of insufficient data despite two attempts to contact the authors. The study characteristics are shown in Table 3.

![Study flow diagram for the systematic review. “wrong language” = in none of the languages listed (English, German, French, or a Scandinavian language).](image)

MUHAMMED ALSHAMARI  *Low-dose computed tomography*  41
Table 3 Study characteristics: Summary of the studies included in the systematic review and the present study.

<table>
<thead>
<tr>
<th>Study</th>
<th>Design</th>
<th>Computed tomography</th>
<th>Abdominal radiography</th>
<th>Reference modality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahn et al 2002, USA</td>
<td>Retrospective, separate review of CT and abdominal radiography</td>
<td>188 (43% male)</td>
<td>52 (range 19–92)</td>
<td>871 (48% male)</td>
</tr>
<tr>
<td>Current study</td>
<td>Prospective comparison within patients, three blinded reviewers</td>
<td>58 (52% male)</td>
<td>65 (range 21–97)</td>
<td>58 (52% male)</td>
</tr>
<tr>
<td>Haller et al 2010, Sweden</td>
<td>Retrospective, separate review of CT and abdominal radiography</td>
<td>76 (51% male)</td>
<td>61 (range 18–89)</td>
<td>86 (45% male)</td>
</tr>
<tr>
<td>MacKersie et al 2005, USA</td>
<td>Prospective comparison within patients, separate reviewers for CT and abdominal radiography</td>
<td>91 (48% male)</td>
<td>48.5 (SD 18.7)</td>
<td>Males 12 mSv, females 17 mSv</td>
</tr>
<tr>
<td>Mangini et al 2008, Italy</td>
<td>Retrospective, focused on CT</td>
<td>57 (51% male)</td>
<td>65.5 (range 19–99)</td>
<td>44 (subset of CT cohort)</td>
</tr>
<tr>
<td>Nguyen et al 2012, Australia</td>
<td>Randomized controlled trial</td>
<td>53 (51% male)</td>
<td>63.6 (SD 17.8)</td>
<td>55 (51% male)</td>
</tr>
</tbody>
</table>

"Low-dose", 4.2 mSv
"Low-dose", 4.2 mSv
The methodological quality of the included studies is summarized in Fig. 5. In general, the result of the index test was known when the reference standard was decided, since this generally depended on the final discharge diagnosis. This increased the risk of bias. There was also a large variation in radiation dose for CT, ranging from low to normal dose.

![Risk of Bias and Applicability Concerns](image)

*Fig. 5 Risk of bias and applicability concerns in the systematic review. The included studies are listed by first author.*
Diagnostic performance
The five studies included in the numerical analysis comprise 470 patients imaged with CT and 1,150 imaged with abdominal radiography. The overall sensitivity for CT varied between 75% and 96%, with specificity ranging from 83% to 95%, whereas the overall sensitivity for abdominal radiography varied between 30% and 77% and specificity was 75–88% (Fig. 6). For the diagnosis of bowel obstruction, the sensitivity for CT varied between 67% and 96%, with specificity of 99–100%. By contrast, the sensitivity for abdominal radiography varied between 48% and 100%, with specificity of 98–100% (Fig. 7). All studies did not provide data for evaluation of both overall performance and bowel obstruction, which explains a lower number of studies in each of these Figures. In a randomized controlled trial by Nguyen et al.\textsuperscript{41} for diagnosis of bowel obstruction, a sensitivity of 82% was reported for low-dose CT and 62% for abdominal radiography, with a specificity of 93% and 92%, respectively (not shown).
Fig. 6 Overall diagnostic performance in the studies included in the systematic review. 95% CI = 95% confidence interval; CT = computed tomography; FN = false negative; FP = false positive; TN = true negative; TP = true positive. The included studies are listed by first author.

Fig. 7 Diagnostic performance in bowel obstruction in the studies included. 95% CI = 95% confidence interval; CT = computed tomography; FN = false negative; FP = false positive; TN = true negative; TP = true positive. The included studies are listed by first author.
Paper 2: Low-dose computed tomography of the lumbar spine: A phantom study on imaging parameters and image quality.

Selection of tube potential (kV)
The highest scored image quality was found at a tube potential of 120 kV (Fig. 8). The results were similar for both tested dose levels, corresponding to an effective dose of 0.5 and 1 mSv. In the statistical analysis, images acquired at a tube potential of 120 kV were scored higher compared to those using 80 kV, but there was no statistical significance between 100 kV and 120 kV (Table 4).

![Graph A](image1.png) ![Graph B](image2.png)

Fig. 8 Scoring of the effect of tube potential on image quality, according to a modification of the European Guidelines for Multislice Computed Tomography (MSCT), of 2004. Image quality was scored of lumbar spine computed tomography (CT) at (A) an effective dose of about 0.5 mSv; and (B) an effective dose of about 1 mSv. R1–R5 = reviewer 1–5.

**Table 4** Image quality score for different tube potentials (80 and 100 kV) compared to the reference tube potential of 120 kV. Values of relative position (RP) and 95% confidence intervals (CIs) are given. Values of RP below zero indicate inferior image quality compared to the reference.

<table>
<thead>
<tr>
<th>Effective dose</th>
<th>80 kV</th>
<th>100 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 mSv</td>
<td>-0.37 (-0.56 to -0.19)</td>
<td>-0.14 (-0.29 to 0.02)</td>
</tr>
<tr>
<td>1 mSv</td>
<td>-0.15 (-0.26 to -0.04)</td>
<td>-0.06 (-0.14 to 0.02)</td>
</tr>
</tbody>
</table>
At direct comparison between the three tube potential levels, the reviewers preferred the images acquired at a tube potential of 120 kV. At about 0.5 mSv effective dose, eight out of ten ratings (five reviewers for axial and sagittal images, respectively) indicated 120 kV as giving the highest image quality. At an effective dose of about 1 mSv, five reviewers preferred 120 kV, with 100 kV as the second best choice. The dose of 80 kV was consistently the least preferred setting.

There was a significant decrease in noise level with increasing tube potential, from 80 kV to 100 kV to 120 kV (p<0.0001). There was no significant difference in CNR between 80 kV and 100 kV (p = 0.14) or between 80 kV and 120 kV (p = 0.5). In the subjective evaluation, the reviewers chose the scans obtained using a tube potential of 120 kV as having the most acceptable noise level compared to 80 kV and 100 kV. A tube potential of 120 kV was consequently chosen for subsequent analysis.

**Selection of reference mAs and convolution filter**

For all dose levels, the medium and medium smooth filter generally received the highest scores, whereas the sharper filter and the smooth filter consistently received lower scores (Fig. 9).

Image quality predictably increased as dose levels increased and scans at the lowest reference mAs levels (10 and 20) received low scores. There was no statistically significant difference between the filters B31f and B41f at reference mAs 30 and 40. The medium filter (B41f) was, however, rated better than B31f at reference mAs 10 and 20 (Table 5). At all dose levels, the sharp and smooth filters received a lower score than the reference filter B31, with RV and 95% CI below 0. The results for the medium sharp filter (B50f) varied. It was rated worse than the reference filter at two dose levels (reference mAs 10 and 30), but there was no significant difference at the other levels (reference mAs 20 and 40).

At direct ranking of the five filters, the medium filter (B41f) was preferred at all dose levels except at reference mAs 30, where the medium smooth filter (B31f) was marginally better compared to the medium filter.
Fig. 9 Scoring of the effect of the convolution filter on image quality according to a modification of the European guidelines for Multislice Computed Tomography (MSCT), which outlines SCT quality criteria for lumbar spine CT, at reference milliampere-seconds mAs (A) 10 mAs; (B) 20 mAs; (C) 30 mAs; and (D) 40 mAs. Included convolution filters range from smooth (B20f) to sharp (B60f).
Table 5 Image quality scores for different convolution filters compared to the reference filter (B31f), and values of relative position (RP) with 95% confidence interval (CI) limits. An RP below zero indicates inferior image quality compared to the reference.

<table>
<thead>
<tr>
<th>Reference mAs</th>
<th>B20f</th>
<th>B41f</th>
<th>B50f</th>
<th>B60f</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-0.08 (-0.22 to 0.06)</td>
<td>0.20 (0.09 to 0.31)</td>
<td>-0.25 (-0.37 to -0.12)</td>
<td>-0.56 (-0.69 to -0.43)</td>
</tr>
<tr>
<td>20</td>
<td>-0.29 (-0.43 to -0.14)</td>
<td>0.01 (-0.07 to 0.10)</td>
<td>-0.02 (-0.17 to 0.12)</td>
<td>-0.46 (-0.59 to -0.34)</td>
</tr>
<tr>
<td>30</td>
<td>-0.40 (-0.53 to -0.26)</td>
<td>-0.07 (-0.16 to 0.03)</td>
<td>-0.23 (-0.34 to -0.12)</td>
<td>-0.61 (-0.73 to -0.49)</td>
</tr>
<tr>
<td>40</td>
<td>-0.49 (-0.62 to -0.37)</td>
<td>-0.07 (-0.20 to 0.07)</td>
<td>-0.12 (-0.28 to 0.05)</td>
<td>-0.52 (-0.66 to -0.38)</td>
</tr>
</tbody>
</table>

Fig. 10 Noise measurements for various convolution filters in the water section of the phantom.
The measured noise levels are shown in Fig. 10. The sharp and medium sharp filters had the highest noise levels, with a significant difference (p<0.0001) compared to the medium smooth filter. There was no significant difference between medium smooth and medium filters for reference mAs 10, 30, and 40 mAs (p>0.5). The reviewers considered the two sharpest filters (B50 and B60) as having too high noise levels. The other filters were considered better, but the medium smooth and medium filters (B31 and B41) were preferred, irrespective of radiation dose level.

Based on the results of our phantom study, we established a protocol for low-dose lumbar spine CT, which is shown in Table 6. The protocol was for a Siemens Somatom As scanner (Siemens, Erlangen, Germany). For other types of scanners, the settings may have to be adjusted slightly.

Table 6 Suggested protocol for a low-dose lumbar spine computed tomography (CT) scan with a Siemens Somatom As scanner.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube potential</td>
<td>120 kV</td>
</tr>
<tr>
<td>Reference mAs</td>
<td>30 mAs</td>
</tr>
<tr>
<td>Collimation</td>
<td>40 x 0.6 mm</td>
</tr>
<tr>
<td>Pitch</td>
<td>1.4</td>
</tr>
<tr>
<td>Rotation time</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Field of view (FOV)</td>
<td>200 x 200 mm</td>
</tr>
<tr>
<td>Convolution filter</td>
<td>B41F</td>
</tr>
<tr>
<td>Automatic exposure control</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Paper 3: Low-dose CT of the lumbar spine compared with radiography: A study on image quality with implications for clinical practice

Image quality assessment
Low-dose CT was scored higher by all reviewers for all image quality criteria compared to radiography except “Sharp reproduction of the cortical and trabecular bone,” which was rated better for radiography (Fig. 11).

Fig. 11 Scores from all reviewers (R1–R5) on all criteria for (A) low-dose computed tomography (CT); and (B) lumbar spine radiography. The full score for each criterion is 1,020 (4 max score x five reviewers x 51 cases).
An example of image quality of low-dose CT in a young patient with normal weight is shown in Fig. 12. Some of the differences in image quality between low-dose CT and radiography in the same patient are shown in Fig. 13. The Figure shows poor visualization of the SI joint in radiography due to gastrointestinal gas, which had no negative effect on low-dose CT images.

Fig. 12 Low-dose computed tomography (CT) of a 27-year-old woman of normal weight. The Figure shows good image quality, which demonstrates the sharp reproduction of different anatomical structures of the lumbar spine.
Fig. 13 Low-dose computed tomography (CT) (left) and radiography (right) of a 73-year-old man. Note the gastrointestinal gas which affected the evaluation of lumbar spine and sacroiliac (SI) joints on radiography, but had no effect on low-dose CT images.
According to the GEE model, low-dose CT has significantly better image quality with regard to seven out of eight criteria compared to radiography, as shown in Table 7.

Table 7 Image quality scoring for low-dose computed tomography (CT) compared to radiography of the lumbar spine. The Table gives odds ratios (ORs) with 95% confidence interval (CI) limits according to the generalized estimating equation (GEE) model for repeated measurements.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Odds ratios</th>
<th>95% CI limits</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Disc profile</td>
<td>1.8</td>
<td>(1.3 to 2.5)</td>
<td>+</td>
</tr>
<tr>
<td>2. Cortical &amp; trabecular bone</td>
<td>0.3</td>
<td>(0.2 to 0.4)</td>
<td>-</td>
</tr>
<tr>
<td>3. Intervertebral foramina &amp; pedicles</td>
<td>4.3</td>
<td>(3.1 to 5.9)</td>
<td>+</td>
</tr>
<tr>
<td>4. Intervertebral joints</td>
<td>139</td>
<td>(59 to 326)</td>
<td>+</td>
</tr>
<tr>
<td>5. Spinous &amp; transverse processes</td>
<td>7.0</td>
<td>(4.3 to 11.2)</td>
<td>+</td>
</tr>
<tr>
<td>6. Adjacent soft tissues</td>
<td>2.9</td>
<td>(2.1 to 4.0)</td>
<td>+</td>
</tr>
<tr>
<td>7. Sacroiliac joints</td>
<td>4.2</td>
<td>(3.2 to 5.7)</td>
<td>+</td>
</tr>
<tr>
<td>8. Absence of superimposed abdominal contents &amp; gas</td>
<td>188</td>
<td>(66 to 539)</td>
<td>+</td>
</tr>
</tbody>
</table>

+ Significantly superior image quality for low-dose CT compared to lumbar spine radiography.
- Significantly inferior image quality for low-dose CT compared to lumbar spine radiography.

When GEE analysis was performed after stratifying data into BMI subgroups, the result for each subgroup was similar to the results for all data shown in Table 7, i.e., all criteria except “Cortical and trabecular bone” were scored significantly better for low-dose CT. Only the criterion “Disc profile” showed no significant difference between low-dose CT and radiography for the obese subgroup.
Kappa values for inter- and intraobserver agreements were generally high for CT (Table 8), except for two criteria, “Cortical and trabecular bone” and “Adjacent soft tissues.” The inter- and intraobserver agreement for radiography was generally low.

Table 8 Inter- and intraobserver agreement in the scoring of eight image quality criteria for low-dose computed tomography (CT) and radiography using free-marginal multirater kappa.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Interoobserver agreement*</th>
<th>Intraobserver agreement**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-dose CT</td>
<td>Radiography</td>
</tr>
<tr>
<td>1. Disc profile</td>
<td>0.87</td>
<td>0.40</td>
</tr>
<tr>
<td>2. Cortical &amp; trabecular bone</td>
<td>0.11</td>
<td>0.55</td>
</tr>
<tr>
<td>3. Intervertebral foramina &amp; pedicles</td>
<td>0.98</td>
<td>0.16</td>
</tr>
<tr>
<td>4. Intervertebral joints</td>
<td>0.92</td>
<td>0.04</td>
</tr>
<tr>
<td>5. Spinous &amp; transverse processes</td>
<td>0.84</td>
<td>0.19</td>
</tr>
<tr>
<td>6. Adjacent soft tissues</td>
<td>0.24</td>
<td>0.12</td>
</tr>
<tr>
<td>7. Sacroiliac joints</td>
<td>0.92</td>
<td>-0.02</td>
</tr>
<tr>
<td>8. Absence of superimposed abdominal contents &amp; gas</td>
<td>0.94</td>
<td>0.17</td>
</tr>
</tbody>
</table>

*Interoobserver agreement was performed for the first observation of all reviewers.

**Intraobserver agreement was performed for the first and second observation of one reviewer.
Pathological findings
There was no significant difference in detection of pathology between the imaging modalities (Table 9), but the reviewers considered pathology to be visualized more clearly and were more certain about their diagnosis on low-dose CT. As an example, a case with unilateral spondylolysis at the L 5–S 1 level (Fig. 14) was diagnosed by four out of five reviewers on low-dose CT, but only by two reviewers on lumbar spine radiography.

Table 9 Pathological findings based on 255 observations (51 cases x five reviewers), including scoring for visibility and certainty.

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Low-dose CT</th>
<th>Radiography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc degeneration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of findings</td>
<td>174</td>
<td>165</td>
</tr>
<tr>
<td>Visibility *</td>
<td>98% (94 to 99%)</td>
<td>90% (84 to 93%)</td>
</tr>
<tr>
<td>Certainty **</td>
<td>98% (94 to 99%)</td>
<td>94% (89 to 97%)</td>
</tr>
<tr>
<td>Intervertebral joint osteoarthritis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of findings</td>
<td>168</td>
<td>150</td>
</tr>
<tr>
<td>Visibility</td>
<td>90% (84 to 94%)</td>
<td>55% (47 to 68%)</td>
</tr>
<tr>
<td>Certainty</td>
<td>92% (87 to 95%)</td>
<td>74% (67 to 81%)</td>
</tr>
<tr>
<td>Spondylosis/diffuse idiopathic skeletal hyperostosis (DISH)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of findings</td>
<td>178</td>
<td>169</td>
</tr>
<tr>
<td>Visibility</td>
<td>94% (89 to 97%)</td>
<td>85% (78 to 89%)</td>
</tr>
<tr>
<td>Certainty</td>
<td>98% (94 to 99%)</td>
<td>88% (82 to 92%)</td>
</tr>
</tbody>
</table>

*Proportion of responses that graded the lesion as clearly seen (95% confidence interval (CI) limits), which was estimated as proportion of clear/total (unclear + intermediate + clear).

**Proportion of responses that graded the diagnosis as certain (95% CI limits), which was estimated as proportion of certain/total (uncertain + intermediate + certain).
Fig. 14 A 64-year-old man with unilateral spondylolysis at the L 5–S 1 level, well demonstrated (line) at low-dose computed tomography (CT) (top). This finding was difficult to detect on lumbar spine radiography (bottom). It is also difficult, based on radiography, to determine whether the spondylolysis is unilateral or bilateral.
In a 71-year-old woman with unilateral pedicle screws at the L 5–S 1 level, low-dose CT showed an acceptable level of metal artifacts and gave better visualization of the screw placement in the L 5 and S 1 vertebrae compared to radiography (Fig. 15).

Fig. 15 A 71-year-old woman with unilateral pedicle screws on the right side at the L 5–S 1 level. Metal artifacts at low-dose computed tomography (CT) (top) were acceptable, with clear visualization of the screw placement in the L 5 and S 1 vertebrae. This was more difficult to visualize on lumbar spine radiography (below).
Dose estimates are shown in Table 10. The dose from the scanogram was estimated at 0.1 mSv and is included in the calculations. The average time to review the studies was 204 seconds for low-dose CT and 152 seconds for radiography.
Table 10 Radiation dosimetry, based on body mass index (BMI), for low-dose computed tomography (CT) and radiography. For CT, the effective dose is given for males and females, respectively. The average volume computed tomography dose index (CTDIvol), dose length product (DLP), and effective milliampere–seconds (mAs) that were displayed on the scanner are also shown. For radiography, the dose area product (DAP) values for each projection are shown, as well as the total effective dose.

<table>
<thead>
<tr>
<th>BMI</th>
<th>CTDIvol (mGy)</th>
<th>DLP (mGycm)</th>
<th>Effective mAs</th>
<th>DAP AP (Gycm²)</th>
<th>DAP Lat (Gycm²)</th>
<th>DAP LS (Gycm²)</th>
<th>Effective dose, CT, m/e/f (mSv)</th>
<th>Effective dose, radiography (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal weight (n=12)</td>
<td>1.47</td>
<td>47.6</td>
<td>17.80</td>
<td>0.50</td>
<td>1.01</td>
<td>1.17</td>
<td>0.7/0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Overweight (n=23)</td>
<td>1.96</td>
<td>60.7</td>
<td>23.70</td>
<td>0.81</td>
<td>1.48</td>
<td>1.22</td>
<td>0.9/1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Obese (n=16)</td>
<td>2.63</td>
<td>78.3</td>
<td>31.10</td>
<td>1.50</td>
<td>2.85</td>
<td>2.46</td>
<td>1.2/1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>All patients (n=51)</td>
<td>2.03</td>
<td>63.3</td>
<td>24.4</td>
<td>0.94</td>
<td>1.72</td>
<td>1.67</td>
<td>1.0/1.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

AP = antero–posterior projection; Lat = lateral projection; LS = lumbosacral projection
Paper 4: Impact of iterative reconstruction on image quality of low-dose CT of the lumbar spine.

Image quality assessment
In the analysis of visual grading data collected from all reviewers regarding all criteria (C1–C7), there was a significant improvement in image quality with IR2, IR3, and IR4 compared to FBP, the reference. The same was found when the bone criteria (C1–C5) and the soft tissue criterion (C6) were analyzed separately. Overlapping CIs indicated no significant differences in image quality between IR2, IR3, and IR4. However, IR5 images were not significantly better than FBP images (Table 11). With regard to the criteria for cortical bone (C1) and trabecular bone (C2), the images with IR2 and IR3 had significantly better quality than FBP, while IR5 images were significantly worse than FBP (Table 11). An example of image quality of low-dose CT of the lumbar spine, reconstructed with FBP and IR2–4 filters, is shown in Fig. 17.

Data for all criteria (C1–C7) and for bone criteria (C1–C5) were stratified by reviewer. There was some variation among reviewers in the evaluation of image quality, mainly for IR3–5, but less for IR2 (Fig. 18). The same pattern of variability among reviewers was noted for bone criteria (C1–C5) after stratification of data by reviewer (not shown).

In the side-by-side visual grading of all image reconstructions from worst to best, IR2, IR3, and IR4 images received the highest scores (Fig. 18).

Noise and dose estimation
The mean overall CTDIvol was 1.70 mGy (SD 0.46, range 1.01–3.83 mGy). The image noise, as measured in the Catphan phantom (The Phantom Laboratory, Salem, NY, USA), was 19 HU in the FPB image and 15, 13, 11, and 9 HU for IR2, IR3, IR4 and IR5, respectively.
Table 11 Scoring of image quality criteria for each reconstruction filter. The odds ratios (ORs) compare IR2-5 to filtered back projection (FBP) (the reference), according to ordinal logistic regression. An OR >1 indicates that the test filter is better than FBP, while an OR <1 indicates that the test is worse than FBP.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Filter</th>
<th>Criterion not fulfilled (%)</th>
<th>Indecisive if fulfilled (%)</th>
<th>Criterion fulfilled (%)</th>
<th>Odds ratio (95% CI)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>All criteria (C1–7)</td>
<td>FBP</td>
<td>34</td>
<td>23</td>
<td>44</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IR2</td>
<td>26</td>
<td>25</td>
<td>50</td>
<td>1.59 (1.39 to 1.83)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR3</td>
<td>24</td>
<td>25</td>
<td>51</td>
<td>1.74 (1.51 to 1.99)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR4</td>
<td>24</td>
<td>28</td>
<td>49</td>
<td>1.68 (1.46 to 1.93)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR5</td>
<td>32</td>
<td>24</td>
<td>44</td>
<td>1.08 (0.94 to 1.23)</td>
<td>NS+</td>
</tr>
<tr>
<td>Bone criteria (C1–5)</td>
<td>FBP</td>
<td>27</td>
<td>23</td>
<td>50</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IR2</td>
<td>20</td>
<td>24</td>
<td>56</td>
<td>1.54 (1.30 to 1.82)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR3</td>
<td>20</td>
<td>24</td>
<td>57</td>
<td>1.55 (1.31 to 1.83)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR4</td>
<td>20</td>
<td>26</td>
<td>54</td>
<td>1.46 (1.24 to 1.73)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR5</td>
<td>27</td>
<td>24</td>
<td>49</td>
<td>1.07 (0.80 to 1.11)</td>
<td>NS</td>
</tr>
<tr>
<td>Cortical bone (C1)</td>
<td>FBP</td>
<td>21</td>
<td>29</td>
<td>51</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IR2</td>
<td>17</td>
<td>23</td>
<td>61</td>
<td>1.83 (1.24 to 2.70)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR3</td>
<td>17</td>
<td>24</td>
<td>60</td>
<td>1.62 (1.10 to 2.38)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR4</td>
<td>19</td>
<td>29</td>
<td>52</td>
<td>1.20 (0.82 to 1.75)</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>IR5</td>
<td>33</td>
<td>22</td>
<td>45</td>
<td>0.55 (0.38 to 0.80)</td>
<td>S−</td>
</tr>
<tr>
<td>Trabecular bone (C2)</td>
<td>FBP</td>
<td>45</td>
<td>22</td>
<td>34</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IR2</td>
<td>32</td>
<td>32</td>
<td>36</td>
<td>1.64 (1.14 to 2.34)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR3</td>
<td>33</td>
<td>30</td>
<td>38</td>
<td>1.60 (1.12 to 2.29)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR4</td>
<td>38</td>
<td>32</td>
<td>29</td>
<td>1.10 (0.77 to 1.58)</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>IR5</td>
<td>52</td>
<td>28</td>
<td>20</td>
<td>0.48 (0.33 to 0.69)</td>
<td>S−</td>
</tr>
<tr>
<td>Intervertebral joints (C3)</td>
<td>FBP</td>
<td>27</td>
<td>23</td>
<td>51</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IR2</td>
<td>19</td>
<td>22</td>
<td>59</td>
<td>2.47 (1.61 to 3.80)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR3</td>
<td>18</td>
<td>23</td>
<td>59</td>
<td>2.52 (1.64 to 3.88)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR4</td>
<td>18</td>
<td>25</td>
<td>58</td>
<td>2.30 (1.50 to 3.53)</td>
<td>S+</td>
</tr>
<tr>
<td></td>
<td>IR5</td>
<td>22</td>
<td>27</td>
<td>52</td>
<td>1.48 (0.97 to 2.24)</td>
<td>NS</td>
</tr>
<tr>
<td>Intervertebral radicular canals (C4)</td>
<td>FBP</td>
<td>15</td>
<td>25</td>
<td>60</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IR2</td>
<td>13</td>
<td>25</td>
<td>63</td>
<td>1.33 (0.84 to 2.09)</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>IR3</td>
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<td>1.72 (1.08 to 2.73)</td>
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<td>Disk profile (C5)</td>
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<td>Soft tissue (C6)</td>
<td>FBP</td>
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<td>Acceptable noise level (C7)</td>
<td>FBP</td>
<td>IR2</td>
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* The test filter (IR) is significantly better/worse than the standard filter (FBP).
** No statistical significance.
CI = confidence interval.
Fig. 16 Axial reconstructions of low-dose computed tomography (CT) of the lumbar spine through the third lumbar vertebra with filtered back projection (FBP) and iterative reconstructions (IR) IR2–5, in a 28-year-old man.
Fig. 17 Evaluation of all criteria (C1–7) with iterative reconstructions IR2–5 for each reviewer (R1–R5). Filtered back projection (FBP) is used as reference. An odds ratio (OR) >1 indicates that the test filter is better than FBP, while an OR <1 indicates that the test filter is worse than FBP.
Fig. 18 Distribution of the scores of (best and second best) image quality according to five reviewers in the side-by-side comparison of images reconstructed with all five filters (filtered back projection (FBP) and iterative reconstruction (IR), IR2–5. The total sum of the scores is 110.
Discussion

In the current thesis project, the aim was to evaluate low-dose CT of the abdomen and lumbar spine, using dose levels comparable with those of radiography, and to compare low-dose CT to radiography. The hypothesis was that CT would give better image and diagnostic information compared to radiography at similar dose levels, and that the dose to the patient would be better used with CT than with radiography. The findings of our studies show that low-dose CT has a superior value, image quality, and/or diagnostic value compared to radiography in the investigation of abdominal pain and the lumbar spine.

Clinical aspects of using low-dose computed tomography

In the paper comparing low-dose CT of the abdomen to abdominal radiography, there was a clear difference between low-dose CT and radiography in identifying patients in need of acute treatment. Abdominal radiography demonstrated low sensitivity for evaluating acute non-traumatic abdominal pain, mostly limited to detecting signs of bowel obstruction or intra-abdominal free gas. Radiography has elsewhere been reported to perform well in the diagnosis of bowel obstruction. A study by Maglinte et al reports fairly similar results for radiography and CT in detection of low or high grade bowel obstruction. However, in the current study, low-dose CT detected not only signs of bowel obstruction, but often the underlying cause of obstruction as well, making surgical decisions easier and avoiding unnecessary delay of appropriate surgical treatment. The benefits of low-dose CT therefore lie not only in its diagnostic value, but also in supporting decision making for management and planning of a treatment strategy. Abdominal radiography has inherent low soft-tissue contrast resolution, making it difficult to detect inflammatory conditions. In the current study, all cases of pancreatitis and diverticulitis were missed by radiography. Radiography can also be misleading in the diagnostic workup of acute abdominal pain and may lead to patients in need of further management being prematurely discharged from hospital, or treatment being delayed by the need of further investigations.

In our study, no patients with presence of free intra-abdominal gas were identified during the study period. However, bile duct gas in one patient was identified readily by low-dose CT, but not by radiography, which is in agreement with a reported case of undetected abdominal perforation with
free gas at abdominal radiography\textsuperscript{50}. Furthermore, several patients received a definitive diagnosis based on low-dose CT, and further treatment could be started without further delay. Low-dose CT, consequently, gives much more information compared to radiography, allowing rapid diagnosis and adequate treatment.

In patients with acute pancreatitis, radiography should not be requested, but this may have happened for various reasons, such as atypical clinical presentation, inadequate clinical evaluation, or no specific lab test for acute pancreatitis performed before radiography.

When patients are lean or emaciated, especially with serious illness and ascites, evaluation with low-dose CT is difficult because all abdominal content is in the low contrast range. Intra-abdominal gas and bowel obstruction can be diagnosed, but any other evaluation is more difficult. Where more detailed imaging is indicated, there is always the possibility to perform a full-dose CT with oral and intravenous contrast media. It is important for both clinicians and radiologists to remember that low-dose CT is not the same as full-dose CT, and the diagnostic possibilities are not the same. Like abdominal radiography, low-dose CT should be used for a limited number of diagnostic questions.

In the systematic review, our study had slightly lower overall sensitivity, but similar specificity, compared to other studies\textsuperscript{43-45} (Fig. 6). This is possibly due to us having applied by far the lowest radiation dose for CT without using contrast media. The overall sensitivity and specificity for abdominal radiography were similar across all studies\textsuperscript{43-45}. For bowel obstruction, both CT and abdominal radiography had relatively high sensitivity and very high specificity in the systematic review. Therefore, it appears that the main advantage of CT, compared to abdominal radiography, is the improved detection of diagnoses other than bowel obstruction. The results of the prospective study are therefore concurrent with the outcome of the systematic literature review.

In Paper 3, on low-dose CT of the lumbar spine, compared to radiography, low-dose CT improved the visualization of most anatomical structures as well as giving observers higher confidence, compared to radiography, in evaluating some common pathologic lesions. For example, low-dose CT can have a better diagnostic value, compared to radiography, in evaluating the lumbar spine area and may reduce misdiagnosis. Pathology was more clearly seen with low-dose CT and the reviewers were more
certain about their diagnosis. Even though these benign lesions are of no clinical concern, easier detection with CT may reflect the benefit of using low-dose CT to visualize small lesions in general, including metastases. Low-dose lumbar spine CT is already in use in many institutions in individual cases, for example when it is difficult to move the patient and to perform radiography. It is often done with suboptimal image quality since there are no obvious or “standard” settings for low-dose lumbar spine CT.

In a paper on imaging, there needs to be mention of magnetic resonance imaging (MRI). Magnetic resonance imaging is a good method in lumbar spine imaging without ionizing radiation. It has been shown to be superior to radiography and CT in the diagnosis of bone marrow edema, medullary infiltration, and disc herniation. However, MRI alone may not be sufficient for a complete understanding of the morphological changes of the skeletal structure, and in such cases, radiography or CT can add information. Furthermore, CT has been proven to be superior for assessment of fracture risk in osteolytic lesions and instability. Magnetic resonance imaging is also more costly and time-consuming, there are some contraindications, and there may be limited availability. All these factors influence the choice of imaging.

Low-dose CT of the abdomen and lumbar spine is easy to perform, and the examination time is similar to radiography. In our department, the radiology staff commonly think of low-dose CT as easier to perform and less troublesome for the patients. Reporting low-dose CT probably takes somewhat longer than reporting abdominal or lumbar spine radiography. The cost for low-dose CT of the abdomen and lumbar spine in our institution is SEK 1,820 (about EUR 198), compared to SEK 1,760 (about EUR 189) for abdominal radiography and, notably, SEK 750 (about EUR 81) for lumbar spine radiography. Low-dose CT causes less wear on the X-ray tube compared to full-dose CT, as lower tube loadings result in lower tube heating. Therefore, low-dose CT can reduce the cost by prolonging the life of the X-ray tube.

**Technical aspects of, and protocols for, low-dose computed tomography**

The protocol used in our study for low-dose CT of the abdomen was: 120 kV, 20 mAs/slice, 0.75s rotation time, FOV 420x420 mm, and 5 mm thickness with no overlap. There were distinct quantum image noise and
streak artifacts in the images, particularly in the pelvic region, which can be considered annoying. Therefore it might be prudent to increase the tube charge to 30 mAs/slice to reduce the noise level at the cost of a slight dose increase. Alternatively, IR can be used to reduce the noise without any dose changes. In our current CT scanners (Somatom Definition AS; 40 channels, and Somatom Definition Flash; 128 channels; Siemens, Erlangen, Germany), the protocol for low-dose CT of the abdomen is: 120 kV, 30 mAs/slice, 0.5 s rotation time, FOV 420x420 mm, and B20f (soft) convolution filter, to minimize the noise level with better visualization of soft tissue.

In low-dose CT of the lumbar spine, tube potential, reference mAs, automatic dose exposure, convolution filter, and even IR were considered in developing a protocol that had a good image quality at similar dosage as used for radiography, i.e., 1 mSv. All reviewers preferred scans with high tube potential (120 kV) (Fig. 8), and image quality was scored highest for 120 kV. Dose reduction was achieved by optimizing the tube current and change, by use of automatic dose exposure and optimal convolution filter. Other studies have used the same approach 43, 53, 54, a combination of reduced kV and mAs 55, or have mainly reduced kV, from 120 to 100 or 80 56, 57.

A setting with reference mAs 40 delivered an effective dose of about 1 mSv to the somewhat small phantom. To be on the safe side, reference mAs 30 could be chosen as the standard setting in low-dose lumbar spine CT to ascertain an effective dose below 1 mSv for the average sized patient weighing 70–80 kg. Different convolution filters ranging from soft to sharp were used to assess the influence of the convolution filter on image resolution and perceived image quality. Images reconstructed with a sharp filter (B60f) are used in daily clinical practice at our institution for standard skeletal CT. The sharp filter reduces image smoothing, making structures such as trabecular bone or cortical bone contours appear sharper. In low-dose CT, however, further reduction of the applied tube charge (mAs) increases image noise, which is inversely proportional to the number of photons absorbed. Consequently, high-resolution techniques using sharp convolution filters dramatically increase the visibility of noise in low-dose CT images. Therefore, the convolution filter had to be changed to a medium filter, for example B41f, for low-dose CT, smoothing the image and reducing visible image noise, to improve the image quality.
**Impact of iterative reconstruction on low-dose CT of the lumbar spine**

The effect of IR was tested to investigate whether IR could improve the image quality of an already established low-dose protocol for lumbar spine CT. The results showed that IR2, IR3, and even IR4, can improve the image quality significantly compared to standard FBP images. In the side-by-side visual grading, there were more individual variations among reviewers. Most of the reviewers preferred IR2–4 to FBP, but reviewers varied regarding which IR level was judged the best (Fig. 18). This may be the result of side-by-side visual grading having a higher degree of subjective assessment since there was no systematic comparison of specific anatomical structures. Furthermore, reviewers could identify some differences in image quality and noise level when they compared images reconstructed by all five filters, side-by-side, on the same screen. However, both times, the assessments of image quality showed higher scores for IR compared to FBP images.

To our knowledge, few studies have been performed previously to evaluate the effect of IR on CT of the spine and there is no previous study that evaluates the use of IR in low-dose CT of the lumbar spine, at an effective dose of about 1 mSv. In CT of the cervical spine, Omoumi et al found that the optimal strength level of IR (SAFIRE, Siemens, Erlangen, Germany) for soft tissues and trabecular bone is lower, while a higher level is better for the evaluation of the intervertebral discs and the neural foramina, i.e., the choice of IR level depends on the anatomical structure. They reported no improvement for cortical bone using IR compared to FBP. Our results for low-dose CT of the lumbar spine show a significantly improved image quality with IR (mainly IR2 and IR3, but also IR4) compared to FBP, with significantly higher scores for sharp reproduction of all selected anatomical structures, i.e., cortical bone, trabecular bone, intervertebral joints, intervertebral radicular canals, disk profile, and paravertebral muscles. Iterative reconstruction images also have a more acceptable overall noise level. Therefore, we can conclude that the optimal strength of IRs in low-dose CT of the lumbar spine seems to be independent of anatomical structures of the lumbar spine.

Consistent with previous studies, our measurements show that an increase in IR level gave a reduction of noise. Others have also shown that there is a shift in the noise spectrum towards lower frequencies.
implies a shift towards an “over-smooth” appearance of the images at high IR levels.

Evaluation of the impact of IR on low-dose CT of the abdomen has not yet been performed in this thesis, but there is a plan to evaluate it in a new clinical study.

**The radiation doses**

For low-dose CT of the abdomen, the effective dose was set at about 1–1.2 mSv, which is in the same magnitude as the effective dose for abdominal radiography consisting of three to four images. This dose level is sufficient for CT to detect fluid-filled and dilated bowel and free intra-abdominal gas. At a low dose level of 1–2 mSv, appendicitis can be diagnosed with CT with the same confidence as at a standard dose of 5–7 mSv. Abdominal radiography in our institution consists routinely of the three images mentioned above. It can be argued whether the multiple projections are necessary. A study by Hoffstetter et al suggests that there is no scientific evidence for the clinical benefit of the supine projection.

In our study, only seven patients (12%) underwent full-dose CT within the first week after initial low-dose CT and one additional patient had full-dose CT after 12 weeks. Full-dose CT would probably have been more common if, initially, only abdominal radiography would have been done, particularly with negative findings. Thus, reduced radiation exposure is accomplished by low-dose CT, reducing further imaging with standard CT at much higher dose levels.

The protocol for low-dose CT of the lumbar spine was derived from our phantom study, as mentioned previously. The dose level was set as the average effective dose of lumbar spine radiography in Sweden, 1.1 mSv, according to a report from 2010. Wall et al reported 0.6 mSv as a typical effective dose in the UK using only two projections, but added that there were large variations between hospitals. Hart et al reported DAP values from lumbar spine examinations indicating effective doses in the range of approximately 0.2–5 mSv. The calculations of effective dose are in general hampered by uncertainties. Effective dose is calculated through multiple steps and calculations depend on a number of approximations. In the current study, the differences in dose for different sizes of patients have been taken into account by using average values for each BMI category.
However, it should be noted that the organ doses used in the calculations are valid for mathematical phantoms equal to a standard patient and should not be used for individual patients. Deviations in the different BMI categories likely lead to different dose distributions and organ doses.

The concept “effective dose” was never meant to be used for individual patients. Any discussion of effective dose must recognize that it is a broad, generic estimate of risk, and that differences of a few mSv do not imply any true differences in biological risk.\(^\text{65-67}\) Rather, radiation risk should be described using broad categories: negligible, <0.1 mSv; minimal, 0.1–1 mSv; very low, 1–10 mSv; and low, 10–100 mSv.\(^\text{67,68}\) Therefore, the effective dose calculated for low-dose CT belongs to the same risk category as radiography.

**Other applications of low-dose computed tomography**

The efficacy of low-dose CT protocols has been assessed in several studies dealing with other organs or pathological entities. Several successful applications of low-dose CT in musculoskeletal imaging have been reported. Low-dose CT has been shown to be a suitable method to implement in the pre- and postoperative investigation of young patients with scoliosis, where a significant dose reduction, compared to standard CT, did not have any negative impact on image quality.\(^\text{55}\) According to Abul-Kasim et al.,\(^\text{69}\) low-dose CT of the spine is a reliable method to assess the accuracy of pedicle screw placement in patients with adolescent idiopathic scoliosis. Low-dose cervical spine CT in patients with blunt trauma has acceptable image quality compared to standard-dose CT.\(^\text{70}\) According to Horger et al.,\(^\text{54}\) low-dose, whole-body CT, compared to plain radiography, in the staging, monitoring, and fracture risk assessment in multiple myeloma patients is a precise and quick diagnostic tool.

Low-dose CT is also well established in clinical practice in other conditions. In a systematic review by Niemann et al., the pooled sensitivity and specificity of low-dose CT for the diagnosis of urolithiasis were 0.966 (95% CI 0.950–0.978) and 0.949 (95% CI 0.920–0.970), respectively.\(^\text{71}\) Screening for lung cancer using low-dose CT has been reported to reduce mortality by 20%.\(^\text{72}\) Low-dose, dual-source CT in coronary angiography in step-and-shoot mode allows, in patients with a regular heart rate, accurate diagnosis of significant coronary stenoses.\(^\text{73}\) Low-dose CT colon-
ography has excellent sensitivity for detection of colorectal carcinomas and polyps larger than 6 mm\textsuperscript{74}.

Several studies have shown the benefits of IR in CT images. Most were designed to minimize the noise level and improve image quality compared to standard FBP. In a previous phantom study, IR (ADIR, Toshiba Medical Systems, Toshiba Corp., Tokyo, Japan) improved image quality significantly and was reported as having the potential to decrease the radiation dose compared to FBP \textsuperscript{75}. In another study, images with IR (ASiR, GE Healthcare, Milwaukee, WI, USA) had lower noise level and improved diagnostic value in abdominal CT \textsuperscript{76}. Iterative reconstruction using IRIS (Siemens, Erlangen, Germany) improved image quality of low-dose chest CT in comparison with standard-dose CT with FBP \textsuperscript{77}, whereas yet another study showed that, in low-dose CT of the lungs, IR (SAFIRE, Siemens, Erlangen, Germany) allowed a dose reduction down to a submillisievert level, but still gave diagnostic image quality \textsuperscript{78}. Iterative reconstruction reduces not only the image noise but also the artifacts from calcifications, which improves diagnostic accuracy of coronary CT angiography in patients with heavily calcified coronary arteries \textsuperscript{79}. Routine use of IR for neuroradiology CT examinations (head, cervical, and intracranial angiography and lumbar spine) is recommended because of a significant dose reduction while preserving image quality \textsuperscript{80}.

Therefore, low-dose CT is already widely in use in the investigation of different organs, whereas standard CT still has a major role in diagnostic imaging due to its high diagnostic value. Further expansion in the use of low-dose CT is likely in diagnostic radiology due to low radiation exposure and also due to the fast evolutionary development of CT techniques.

**Study design and choice of statistical methods**

The data in subjective image quality assessment studies are an ordinal data type. Each image is graded based on one or more criteria by a number of observers who select a score reflecting the general quality of the image or the scan based on a specific criterion such as the visibility of a certain anatomical structure. Well-defined criteria, such as the EU criteria \textsuperscript{18}, are often used, and the score is typically set on a scale with a limited number of steps where, for example, 0 denotes the lowest and 4 the highest category. However, it can be difficult to select an appropriate statistical method. Sometimes, the ordinal variables may be treated as continuous variables to

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perform the statistical analysis. Unfortunately, this approach may yield misleading results. Although the values on the scale have a natural ordering, there is no guarantee that the difference between 0 and 1 is equivalent to that between 1 and 2 or between 3 and 4.

In Paper 2, a method described by Svensson was employed. The observations, ordinal data of visual grading, were linked to pairs of observations, consisting of the image with the new CT setting, tube potential, and convolution filter, compared to the reference. The systematic change in position for the group with the new setting and the group with the reference setting is described by the empirical measure RP, which can have a value between –1 and 1. A positive value of RP indicates that the group with the new setting is better than the reference, and vice versa.

In Papers 3 and Paper 4, the ordinal data of image quality was analyzed using the GEE model and VGR, respectively. They are ordinal logistic regression models that have recently increased in popularity as a useful statistical method for analyzing image quality. From these ordinal logistic regression models, ORs with 95% CIs could be estimated to give a measure of the associations. An OR of 1 is interpreted as no difference in image quality between the test and the reference.

There was an obvious interobserver variation in scoring in Paper 4, which can be explained by the small differences in image quality between the various IR levels. Furthermore, visual grading analysis is based on a subjective assessment of image quality, which could be affected by other factors such as rater experience and personal preference. For subjective evaluations, the fact that different observers have different opinions regarding image quality cannot be ignored. Furthermore, images reconstructed with strong levels of IR (SAFIRE) have an “over-smooth” appearance, which may affect the image quality assessment depending on how familiar the reviewers are with that appearance. The reason for using a fixed level in the lumbar spine to be evaluated in Paper 4 was to ensure that all reviewers assessed the same anatomical structures of the lumbar spine.

Strengths of Papers 2–4 include the fairly high number of reviewers, with five reviewers taking part in this study, providing a wide range of experience in evaluating image quality. Paper 3 included tests of intraobserver and interobserver agreement and an evaluation of whether BMI was a
confounder. In all the clinical studies (Papers 1, 3, and 4) in the current thesis, we had a relatively high number of patients, more than 50, with a wide age range and from both sexes, to minimize any risk of bias due to patient-related factors.

Limitations
In Paper 1, one limitation was that the diagnosis from the medical records was used for the reference standard, and there is a risk that that diagnosis is affected by the radiology report. The sample size was large enough to show a significant difference in sensitivity between the two methods, but the sample did not include any cases of bowel perforation or free abdominal gas which is one of the common causes for acute abdomen. Moreover, the protocol for low-dose CT was not evaluated in children and cannot be directly applied for acute pediatric abdomen before further studies have been conducted. Finally, the cost effectiveness is still unclear and has not been addressed in this study. However, a recently published study shows that a routine contrast-enhanced CT cannot be considered cost-effective in acute abdomen. From an economic perspective, CT should be reserved for patients who need it purely on clinical grounds.

The main limitation of Paper 2 was the somewhat small size of the phantom. According to a previous study using a water-filled, 30 cm wide phantom with a cross-sectional area of 706.5 cm², the absorption of X-rays corresponded to that of an average adult person. Therefore, the phantom used in the current study, which had a cross-sectional area of 608 cm² and was not only water-filled as it contained an ovine lumbar spine with the surrounding muscles, can be considered to correspond to a small to medium-sized adult. However, this was considered when choosing settings for an effective dose lower than 1 mSv. Another limitation was the use of an ordinal scale for scoring image quality.

In Paper 3, one of limitations was that the major part of the sample was referred from primary health care with a history of low back pain without any known serious underlying condition. The expectation of pathological findings was therefore low compared to more advanced cases, such as trauma, known malignancy, or skeletal metastasis. To our knowledge, application of low-dose lumbar spine CT is new, and its impact on diagnosis and patient management has yet to be determined. Secondly, the result is mainly based on a subjective image quality assessment.
Another limitation was the difficulties in comparing image quality of two different modalities. However, the purpose of the current study was to test the capability of the new method to demonstrate different anatomical structures, compared to the standard method, radiography, as a minimum requirement of the diagnostic method. The fact that all observers were consistent in their assessments indicates that this comparison, between 2 different kinds of images, was applicable.

A limitation of Paper 4 is that the result is mainly based on a subjective image quality assessment. Another limitation is that pathological findings and diagnostic performance were not assessed. Thirdly, we used IR from Siemens (SAFIRE), while the impact of IR and its optimal level for low-dose CT of the lumbar spine may differ depending on the IR algorithm developed by different manufacturers.

**Clinical implementation**

- In our institute and many other institutes in Sweden, low-dose CT of the abdomen, rather than abdominal radiography, is routinely used in the investigation of acute abdominal pain. It is mostly performed to evaluate bowel obstruction, free gas, and constipation. It has almost entirely replaced radiography in the work up of acute non-traumatic abdominal pain in adults. Radiography is still the first choice examination for children.
- Low-dose CT of the lumbar spine was recently implemented in our institute as a routine instead of lumbar spine radiography mainly for inpatients and for patients referred from the ED. A presentation of Papers 2 and 3 of low-dose CT of the lumbar spine was made to our orthopaedic surgeons at the Department of Orthopedics, Örebro University Hospital. They were positive about adopting the new routine, i.e., low-dose CT for lumbar spine imaging, instead of radiography.

**Future perspectives**

- There are several commercially available new techniques and methods from different manufacturers, to reduce CT radiation dose. They need to be tested in clinical studies before implementation. However, radiologists in cooperation with medical physicists
can also manage radiation dose by adjusting CT settings and optimizing CT protocols so that diagnostic needs are met.

- The effect of IR algorithms on low-dose CT of the abdomen should be tested as IR algorithms improve image quality in standard abdominal CT.

- Further research on evaluation of the diagnostic accuracy of low-dose CT of the lumbar spine is warranted, especially for the detection of lesions such as skeletal destructions and fractures.

- Low-dose CT image quality or diagnostic value can be tested in other parts of the human body to develop new applications for low-dose CT, such as low-dose CT pelvimetry or low-dose CT urography.
Conclusions

- Low-dose CT has higher diagnostic accuracy compared to abdominal radiography. Based on performance, and where logistically possible, it should replace abdominal radiography in the diagnostic workup of adult patients with acute non-traumatic abdominal pain.

- Low-dose CT of the lumbar spine at similar dose levels as radiography, i.e., 1 mSv, has superior image quality to lumbar spine radiography as it can give more anatomical and diagnostic information compared to lumbar spine radiography and could therefore replace it in daily clinical practice.

- It is possible to develop a new protocol for CT of the lumbar spine at 1 mSv, by considering different strategies, for example tube potential, reference mAs, convolution filters, and IRs.

- In skeletal imaging with low-dose CT, a medium filter has higher image quality compared to a hard or sharp filter and is therefore recommended.

- Iterative reconstruction (SAFIRE) at levels 2, 3, and 4 improves image quality of low-dose CT of the lumbar spine compared to filtered back projection.
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