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Dose Optimization and Reduction in CT of the Head and Neck, Including Brain

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9.1 Dose Optimization and Reduction in CT of the Head (Brain)

9.1.1 Introduction

Since its introduction in the 1970s, CT has played an increasingly important role in the imaging diagnosis of a variety of disorders. This is especially true in the field of neuroradiology, where CT made direct visualization of neurological anatomy possible for the first time, thereby revolutionizing diagnostic imaging.

However, it is well known that the CT-induced radiation dose is considered high compared with other (X-ray based) imaging techniques. For a CT examination of the same region, various authors have reported different dose values. This difference is due to variations in applied scan protocols, and the different choice of units of measurements in which they expressed the dose. This hindered comparison between studies and makes the correlation of CT with other radiological procedures difficult. In routine practice, about 30%–40% of all CT studies are studies of the head or brain, with a mean effective dose ranging from 1 mSv to 5 mSv (Van Unnik et al. 1997).

Although magnetic resonance imaging (MRI) was expected to reduce the overall frequency of CT (especially in neuroimaging), this has not been the case (Rehani and Berry 2000). Indeed, the advent of helical and multidetector helical CT (MDCT) with rapid acquisitions times and new diagnostic fields (e.g. CT angiography, perfusion CT) has led to a further increase in CT examinations: over the last 10 years CT has more than doubled its contribution and is now responsible for 47% of the collective dose from medical X-rays in the UK (Hart and Wall 2004). This evolution has spurred a growing interest in CT dose optimization and reduction in recent years.

MRI has superseded CT for examining the head, neck and spine, many parts of the musculoskeletal system and it offers an alternative to CT in the abdomen and pelvis. Nevertheless, the higher cost and the lesser availability of MRI remain a problem. Therefore, CT remains the method of choice for evaluation of post-traumatic injuries of the head, spine, thorax, abdomen and pelvis, for detection and characterization of parenchymal lung disease and for staging of almost all solid malignancies, including lymphomas. In the evaluation of cerebrovascular pathology, recent developments with diffusion and perfusion techniques have given MRI a higher sensitivity and specificity, although CT still plays a major role

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in the evaluation of these disorders, due to its high sensitivity in the detection of intracranial haemorrhage, faster image acquisition, wider availability, lower cost, ease of use and fewer contraindications (Rehani and Berry 2000).

In CT, the effect of changing dose (e.g. by changing tube current or mAs settings) on image quality is sometimes difficult to assess, as CT is a digital technique in which image acquisition and display are not related, i.e. the "uncoupling effect". Thus, unlike conventional plain-film radiography, excessive exposure will not result in overexposure of images and degradation of image quality. As a result, significant variations have been observed between individual scanners in the typical patient doses for common CT examinations (Van Unnik et al. 1997; Clark et al. 2000). Multiple studies concentrating on dose reduction showed that low-dose CT is possible in high-contrast imaging, e.g. imaging of the lungs, without loss of diagnostic information (Zwirewich et al. 1991). It remains however unclear if dose reduction is also possible in areas with low contrast differences, such as the intracranial brain structures.

This is nevertheless an important issue, since patients who are examined or treated for complex or chronic brain disease (e.g. malformation, tumours, trauma and cerebrovascular disease) often undergo multiple CT studies over time. This also applies, for instance, to children with hydrocephalus with malfunctioning ventricular shunts. Although initial CT studies are oriented towards identification of subtle changes of intracranial structures, the main purpose of those control studies is to identify complications and gross morphological changes. As this often involves structures with high contrast or large structures (e.g. follow-up of haemorrhage or ventricular size), a reduction of "standard" scan parameters to lower dose settings seems possible in these CT studies (Cohnen et al. 2000).

9.1.2 Typical Dose Values in Head CT

Two large-scale surveys regarding the use of brain CT were undertaken in the late 1980s and early 1990s in the USA (McCrohan et al. 1987; Conway et al. 1992). These involved more than 250 CT scanners of different models. The average radiation dose in a standard CT brain examination in adults was hereby investigated at that time. Results showed that for brain CT examinations, the tube voltage (kV) was consistent at 120–140 kV for a given manufacturer and model. Slice thickness, slice spacing (increment) and total scan length and therefore the number of slices were also quite consistent and constant. However, tube current (mAs) was one of the most variable parameters between different CT systems and even for systems of the same manufacturer and model. For most systems, the minimum and maximum mAs values used for CT brain examinations differed by a factor of 3–4. This resulted in a dose variation of a factor of 2 or more for a typical ("standard") head examination for a given model of CT scanner. In these earlier surveys, the multiple-scan average dose (MSAD) was used as the dose descriptor. For most of the systems, the MSAD at the midpoint on the central axis of a standard dosimetry phantom varied between 22 and 68 mGy, but doses as high as 140 mGy were noted. Furthermore, the registered dose sometimes varied by a factor of 2 or more between identical CT units. The MSAD can be compared with the later introduced and now more commonly used CT dose index (CTDI), since both are based on the integral of a single-section dose profile, whereby CTDI may differ from MSAD with a variation of 10% up to 25%, depending on the used slice thickness and spacing. Both measurement units give a simple estimate of the dose delivered during the entire CT procedure to the region of the central section (Conway et al. 1992). The authors of these two large surveys concluded that these wide dose ranges indicated that dose has the potential to be reduced by careful selection of standard CT techniques.

Overall, variations in dose can result from differences in the user's choice of technique (desired image quality) or from actual differences in scanner performances (caused by differences in collimation, filtration or scan geometry). "Users of CT systems should be aware of radiation dose delivered with CT, dose ranges associated with different systems and doses delivered by their particular unit. This requires that dose performances of CT systems should be assessed by means of a protocol that allows comparison of data collected for identical and/or different units. To use CT appropriately, a facility should consider dose as well as image quality in selecting optimal techniques for typical modes of operation" (McCrohan et al. 1987; Conway et al. 1992).

In 1990, The International Commission on Radiological Protection introduced the dosimetric quantity "effective dose" that provides a direct relationship to the radiation hazard (ICRP 1991, report

60). In the context of regulations and radioprotection, this quantity of effective dose is probably the most relevant way in which to express and compare "the dose given to a patient" from different imaging procedures. It takes account of the distribution of dose amongst the radiosensitive organs in the body by summing the individual organ doses, having weighted each one according to the relative sensitivity of the organ to radiation-induced somatic or genetic effects. Effective dose is expressed in a special SI unit, Sievert (Sv). The risk for a given effective dose decreases with increasing patient age at exposure, since somatic effects, being delayed for many years or even decades after the exposure, will have a reduced opportunity for expression after X-ray exposure on the elderly. Furthermore, genetic effects are of no consequence for patients beyond their reproductive years (Wall and Hart 1997).

Although the main scan parameters, tube current time product (mAs) and tube voltage (kV), are relatively high in CT studies of the head in comparison with other CT studies, the effective dose associated with head CT scans is considerably less than that of abdominal or chest CT examinations (Van Unnik et al. 1997). Like the initial US surveys, similar surveys were done in the UK (Shrimpton et al. 1991), which showed that minimum and maximum doses for brain CT examinations could vary by a factor of up to 11-fold. Inherent differences in scanner design have been shown to contribute to this dose variation between models by up to a factor of 3 at most. Hence, much of the wider variation observed was caused by difference in local scanning technique and parameters employed. They conducted a survey in which the CTDI was measured in scanners of a large number of English hospitals and effective doses of various standard examinations were calculated using organ-dose conversion factors. A Dutch survey showed similar findings (Van Unnik et al. 1997) and confirmed that the greatest single variable that determines the patient dose is the way the scan is performed. They found mean effective doses in a CT brain examination ranging from 0.8 to 5 mSv, whereby the large dose distribution can be explained in part by the fact that a repeat scan with administration of iodine contrast doubles the dose. Although the reason for administration of contrast generally depends on the clinical situation, a large variation was shown, whereby in some hospitals nearly all patients were scanned without contrast and in others nearly all patients were scanned with contrast. Despite the clinical introduction of MRI more than 10 years ago, this Dutch survey showed that CT of the brain still represented about 35%–40% of all CT examinations in 1997.

This is comparable with a local survey in our department which showed in 1997 that 37% of all CT examinations were cranial ones. Nevertheless, the number cranial CT exams in our department is declining, comprising 41% and 39% of all CT examinations in 1991 and 1995, respectively. This further lowered to 31% and 30% in 2002 and 2003, after introduction of an MR unit. This declining trend in the use of CT of the head (in favour of MRI) is also reflected by the fact that in the first US survey of 1987, more than 50% of all CT examinations were brain CT's (McCrohan et al. 1987).

In 1998, the European Commission (EC) proposed reference dose quantities or levels for CT (EC Working Document, EUR 16262, 1998), based on the weighted CT dose index ($CTDI_w$, mGy) and dose length product (DLP, mGy·cm). These EC dose reference levels (DRL) for CT represent the third quartile values of mean CT dose recorded for an adequate sample of patients and have proved to be useful as reference dose levels in previous surveys. For CT of the head, these reference values are 60 mGy for the $CTDI_w$ and 1050 mGy·cm for the DLP. This corresponds to a "reference" effective dose for CT of the head of 2.2 mSv (Clark et al. 2000). The EC working document gives data that allow the values of DLP to be converted into effective dose by using conversion factors for broad regions of the body. For cranial CT this conversion value is 0.0021 mSv/(mGy·cm). These reference doses are, in effect, investigation levels related to average practice, since they are derived from mean doses and are not applicable to individual patients. It is accepted that the use of these levels should not interfere with good clinical practice, but that they can be useful for comparing samples of patients from different centres. The goal or rationale behind these reference levels is the following: by setting the reference level on the third quartile values, the 25% of hospitals or departments contributing to the highest dose would review their procedures and reduce their patient doses accordingly. This philosophy is now accepted in Europe. A local survey in Northern Ireland showed that comparison of effective dose was more useful than usage of the proposed EC reference levels for routine CT examinations of the head, chest, abdomen and pelvis. They concluded that revision of the mAs values will produce a significant reduction in patient dose, without compromising image quality (Clark et al. 2000).

9.1.3 Modalities for Dose Reduction in Cranial CT

Scan parameters of "standard" examination protocols in cranial CT are usually implemented by manufacturers, and are oriented toward attaining the best image quality in order to meet the highest diagnostic criteria. For decades, neuroradiologists have welcomed the advances in depicting neuroanatomy by new imaging techniques and accepted physics theories and vendor advice that high signal-to-noise ratio concerns justify using recommended CT dose rates (Fox 2004). Indeed, image conspicuity for brain structures such as grey and white matter is in the category of "low contrast". Nevertheless, many neuroradiologists do not pay attention to the doses used in their own CT suites. Their technologists usually receive training from the CT vendors, which do not like to demonstrate routine work at minimal dose, because images with more noise show a vendor's product to be inferior (Fox 2004).

Only a few studies have focused on the possibility of lowering the dose for CT of the head.

In a study (Cohnen et al. 2000) to assess image quality changes on CT scans of the head using a formalin-fixed cadaver, the radiation dose was reduced by lowering both tube current and kilovoltage, and this on two different CT machines, both in conventional sequential mode and (single-slice) helical scanning mode. Five experienced readers independently evaluated subjective image quality, whereby no observable differences in image quality between scans obtained with doses from 100% ("standard mode") to 60% of standard settings were noted. "Standard mode" for sequential mode was 135 kV–270 mAs and 130 kV–315 mAs for two different scanners, and 120 kV–185 mAs and 130 kV–157 mAs for helical scanning, with these two machines, respectively. Image noise was substantially higher in the cerebellar parenchyma (posterior fossa) than at the centrum semiovale (supratentorial level), suggesting the influence of petrous and facial bones. This was more obvious on low-dose images. In this study a linear inverse relation between image noise and dose was found. There was only a general assessment of subjective image quality of a cadaver head and no correlation with a clinical situation. Scans produced with a dose that was more than 50% reduced in comparison with "standard" settings were judged uninterpretable.

In a recent study (Mullins et al. 2004) of 20 elderly (> 65 years) patients with a 4-MDCT helical CT exam of the head for routine indications, with settings of 140 kV, 170 mAs, 1 s scan time and pitch factor of 0.75 ($CTDI_w$ of 65 mGy), the scan was repeated for a limited volume by covering four 5-mm-thick images at 90 mAs ($CTDI_w$ of 34 mGy, other scan parameters identical) at four levels: posterior fossa, middle cranial fossa, corona radiata and centrum semiovale, with a dose reduction of 47% (Fig. 9.1). The conspicuity between grey matter (GM) and white matter (WM) was not significantly different between the two dose groups. Main GM contrast-to-noise ratio (CNR) was 22% higher in the 170-mAs group, which was statistically significant, but all 90-mAs images (although somewhat noisier) were considered to be of acceptable diagnostic image quality and sufficient resolution, as rated by three experienced neurora-

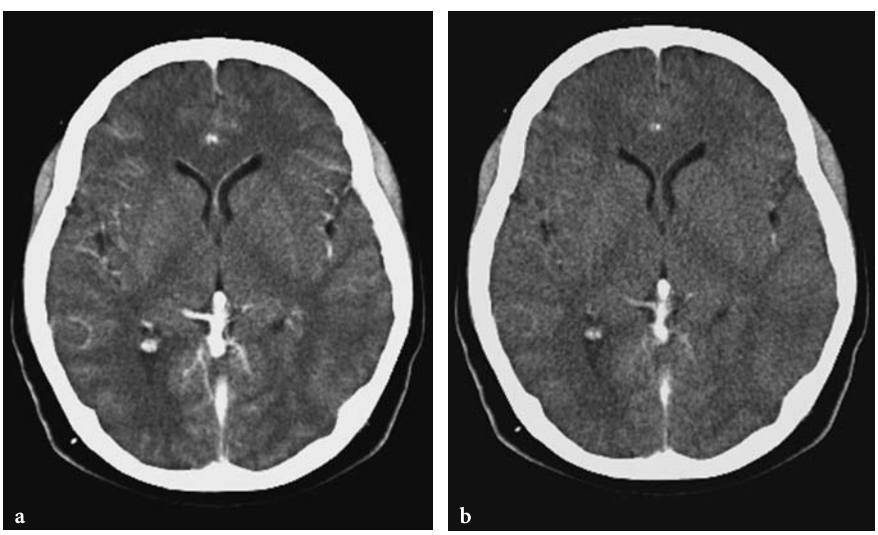


Fig. 9.1a, b. CT images of a 43-year-old woman with persistent headache for 3 weeks show normal brain struc-tures at the level of the basal ganglia. Standard brain CT after intravenous iodium contrast with a 6-MDCT at 130 kV, 280 mAs, 1 s rotation, CTDI = 61.2 mGy, comparable to the "EC reference level" and standard dose level of the study of Mullins et al. (2004). Calculated effective dose of the "standard" CT exam is 2.13 mSv; DLP = 820 mGy·cm. **a** A 5 mm axial image with "standard" dose at 280 mAs and **b** an additional 5 mm axial image at low dose at 140 mAs: with 50% dose reduction the image is somewhat noisier but there is a clear delineation of the anatomical structures

diologists. They indicate that in a hospital with an active neurological intensive care unit and a stroke unit, it is not unusual for some critically ill patients to receive multiple (sometimes daily) CT exams of the head for a period of some days or even weeks. The indications for these scans are frequently gross imaging findings, but which may change and affect management decisions: traumatic or non-traumatic haemorrhage (Fig. 9.2), aneurysm rupture, stroke and hydrocephalus (Fig. 9.3). For younger patients (and children) the difference between scans with a $CTDI_w$ of 65 mGy and of 34 mGy seems significant, especially when this is repeated several times in a short period. Recommendation of a low-dose technique for initial workup seems inappropriate (at present), since there is no scientific backup from other low-dose studies showing its potential to detect subtle pathology (e.g. lacunar infarctions) accurately. However, objective measurements showed no statistically significant difference in GM–WM conspicuity between standard and low-dose (about 50% less) images, which is a far more subtle distinction in terms of Hounsfield units than the conspicuity of most lesions (Mullins et al. 2004).

Another recent study (Britten et al. 2004) reached similar results: they added spatially correlated statistical noise to standard CT images of the head to simulate exposure reduction of up to 50% in 23 elderly patients (> 69 years). In this way, at 120 kV, starting from an initial scan at 420 mAs, they simulated images at 300, 260 and 210 mAs. They used the presence of periventricular low-density lesions as an

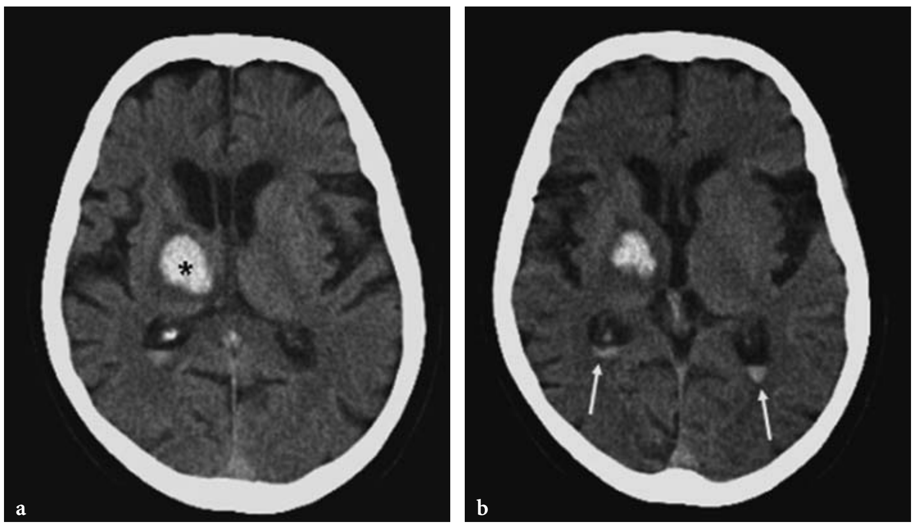


Fig. 9.2a, b. Control brain CT study with 50% dose reduction (CTDI of 30.6 mGy) in comparison with "standard" settings by halving tube current in a 69-year-old woman with right-sided thalamus haemorrhage, 1 day after admission to the intensive stoke unit because of progressive somnolentia (same scan protocol as in Fig. 9.1b). **a** Axial 5 mm images show clear visualization of haemorrhage (*asterisk*) and **b** the presence of an intraventricular extension with small blood-liquor levels (*arrows*) in both occipital horns. Calculated effective dose of low-dose CT exam is 1.12 mSv; DLP = 432 mGy·cm

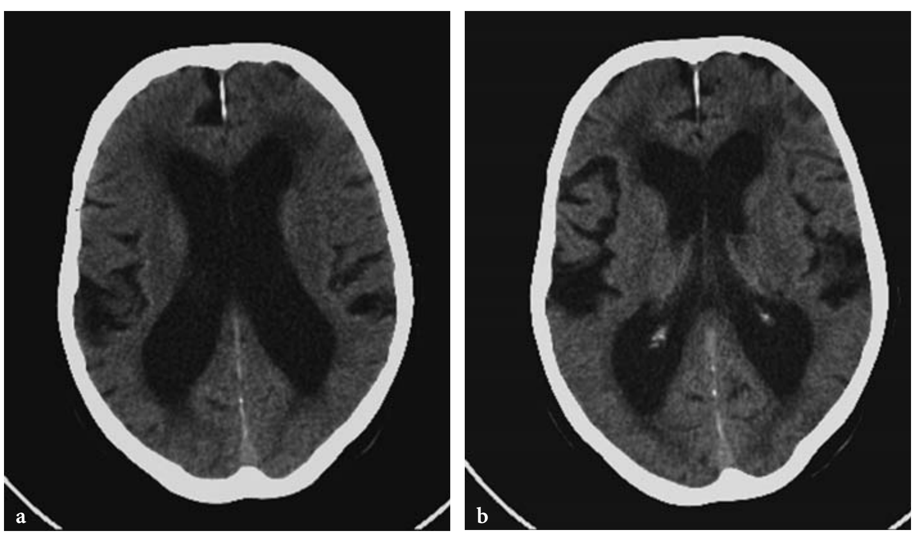


Fig. 9.3a, b. Follow-up brain CT study at low dose (CTDI of 30.6 mGy) in a 79-year-old woman with (normal pressure) hydrocephalus. Low-dose axial CT images are of sufficient quality to compare the dilatation of both lateral ventricles (**a** and **b**) with previous CT studies. Calculated effective dose of low-dose CT exam is 1.05 mSv; DLP = 405 mGy·cm

example of the effect of simulated dose reduction on diagnostic accuracy, which was not lowered significantly even with 210-mAs images (50% dose reduction), and used visualization of the internal capsule as a measurement of image quality, which was obviously lowered with low-dose images.

A drawback of these two low-dose cranial CT studies is the small number of patients that were studied: the question remains as to whether the same would be achieved in the total population. A reduction of sensitivity can be expected in the total population, given the extremely low number of patients (*n*= 22 and 23) studied.

A third recent study (Gündogdu et al. 2005) analysed the effect of various tube current settings in an attempt to optimize the image quality and dose for adult cranial CT in 60 patients. They examined three reference levels (posterior fossa, basal ganglia and centrum semiovale) and evaluated subjective image and noise quality scores and quantitative noise measurements. At 50% decreased dose protocol, starting from a CTDI of 58.2 mGy for the posterior fossa and 48 mGy supratentorially, there was no poor quality score at any level; at nearly 60% decreased dose protocol, poor quality scores were much higher, especially in the posterior fossa.

The importance of these three recent studies (Britten et al. 2004; Mullins et al. 2004; Gündogdu et al. 2005) is that they indicate that it is clinically feasible to lower the dose for "standard" cranial CT examinations and that a dose reduction up to 50% seems to give no significant image quality loss. Their limitation is that they evaluated only morphologically normal anatomical brain areas and the question remains as to how much the resolution of low-contrast lesions will be affected by low-dose protocols.

In CT of the brain, the lens of the eye is of particular concern as cataract formation is a well-documented result of radiation damage. The use of a different scan plane (different beam angulation by gantry angulation) to avoid the orbits has been shown to reduce the eye lens dose by 87% (Yeoman et al. 1992), without affecting the severity of posterior fossa artefacts (beam hardening by the petrous bones). An international questionnaire survey in this study in more than 180 hospitals in the UK, USA, Australia and Europe showed that only 32% of the hospitals routinely avoided the eye lens during cranial CT.

In 2001, Brenner et al. reported an estimated lifetime cancer mortality risk of 0.18% for paediatric abdominal CT and 0.07% for paediatric head CT, both of which were approximately 10 times higher than the same risks for adults. These results are debatable (they are estimations) and the authors stressed that these numbers still represent only a small increase in cancer mortality over the natural cancer background rate; nevertheless, their study indicates the importance of adapting radiation exposure in CT to a substantially lower level for children and not just applying adult scan parameters to the paediatric population, a method that was common practice until that period (Rogers 2001). Image quality in CT (e.g. CNR) depends primarily on the detected X-ray fluency; consequently, the technique factors used in paediatric CT can and should be reduced in comparison with adult technique factors, because smaller patients attenuate fewer X-rays. Thus, equivalent image quality can (and must) be produced at lower dose levels. Moreover, the values for energy imparted at CT in paediatric patients are generally lower than in adults, but the smaller mass of children (and the longer expected lifetime) causes the corresponding effective dose to be higher in children than in adults undergoing similar CT examinations (Huda et al. 1997).

Like in adults, cranial CT is the most common CT examination in children. In neonates and young children, about 25%–30% of the active bone marrow is present in the skull, whereby in adults this is only 5%–10%. The marrow-absorbed dose in a 6-year-old phantom for a paediatric cranial CT is reportedly higher than that for chest or abdominal CT (Fearon and Vucich 1987). In 1999, a paediatric brain CT study showed that a lower tube current can be used for children with no difference in image quality (Chan et al. 1999). They compared cranial CT at 120 kV with 250 or 200 mAs (age above or under 5 years; $n=53$) with that at 150 or 125 mAs (according to age; $n=47$) and found no difference in image quality scores at seven different anatomical areas, whereby a dose reduction of 37.5% and 40% was reached (Fig. 9.4). Similar results were shown by comparing paediatric cranial CT at 140 kV and 180–240 mA (according to age) with a lower dose at 90–130 mA (Shah et al. 2005): a 45%–50% tube current reduction was possible without any significant effect on image quality and reader confidence in the level of detail available to reach a diagnosis.

Wong et al. proposed using the maximum antero-posterior diameter (MAPD) of the child's head, measured on a lateral scout view at the start of the examination, as a good criterion for tube current selection (Wong et al. 2001). Another practical proposition is the use of CT technique charts (Boone et al. 2003)

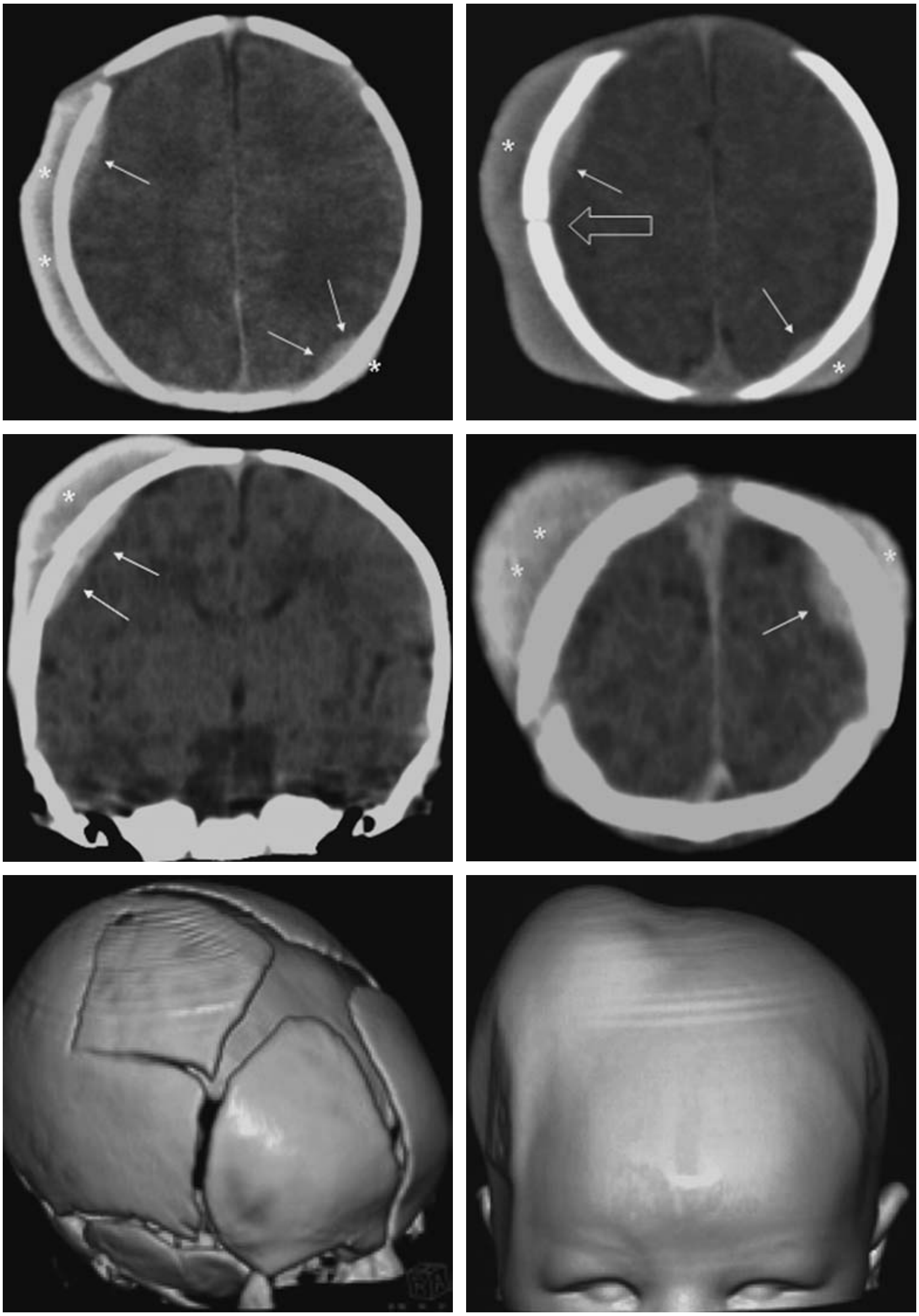


Fig. 9.4a–f. Male newborn with gradual soft-tissue swelling on the right side of the head after difficult delivery assisted with vacuum extractor. Standard skull X-ray showed linear parietal fracture. A 6-MDCT helical brain exam was performed with adapted paediatric protocol: 110 kV, 125 mAs, 1 s rotation, CTDI vol of 23.75 mGy, pitch factor of 1. Calculated effective dose was 5.9 mSv. **a**, **b** Axial 5 mm images showing bilateral epidural haematomas (*arrows*), skull fracture (*open arrow*) and large (right) and small (left) cephalhaematomas (*asterisks*). **c**, **d** A 5 mm coronal MPR image and 5 mm axial image showing communication of the right epidural haematoma with right cephalhaematoma trough skull fracture (*open arrow*); there is no brain oedema or important mass effect of the hematomas. **e**, **f** Volume rendering images with bone setting (**e**) show the extent of the linear, angle-shaped right parietal bone fracture and with soft-tissue settings (**f**) show nicely the extent of the cephalhaematomas

where, depending on the child's (head or trunk) diameter or circumference, a tube current reduction factor is given, starting from the tube current used in adults, reducing the radiation dose and preserving the contrast-to-noise ratio. These factors were calculated based on physically measured data in phantom cylinders of different diameter. Because of the exponential relationship between patient thickness and X-ray attenuation, very large dose reductions are proposed in the smallest children (Boone et al. 2003).

Since children have less thick and less dense (less calcified) bones, it seems logical to use a lower tube voltage to lower the dose; for example, lowering the tube voltage from 120 to 80 kV gives a dose reduction of 75%. Especially for young children and infants the use of 100 kV as the tube voltage in cranial CT seems sufficient (Chan et al. 1999).

9.1.4
Conclusion

The goal of radiology is accurate, timely and clinically relevant diagnosis. Reducing patient dose by limiting X-ray exposure has the inevitable consequence of increasing noise in CT images. The key question is to identify the minimum X-ray exposure, i.e. the "poorest" image quality, required for a given examination and pathology (Britten et al. 2004). Recent studies have shown the possibility of reducing the radiation in adult cranial CT up to 50%, without significant loss of image quality, but they mostly studied only normal anatomical brain images. The question remains as to whether this low-dose technique still holds for specific brain pathologies, which frequently give a "low contrast" difference in comparison with normal brain tissue. The ability to add noise by computer simulation to real CT studies offers the prospect of being able to perform large-scale studies to evaluate diagnostic accuracy as a function of reducing the dose: in this time of picture archiving and communication systems (PACS), every radiological site has access to a substantial archive of clinical pathological cases in order to study the potential of reaching an objectively judged minimum dose level.

In certain clinical circumstances and patient populations, a trade-off between reduced radiation dose and image quality may already be acceptable, without sacrificing diagnostic accuracy. Low-dose brain CT may be appropriate when routine follow-up of initial high contrast findings is required (e.g. hydrocephalus or haemorrhage). Also, hospitalized patients who require frequent serial CT scans for neurological or neurosurgical care may also benefit from this low-dose scanning. Finally, it is important to lower the dose parameters for paediatric head CT, since children are more sensitive to radiation-induced damage. Nowadays, all CT vendors offer specific paediatric scan protocols with adapted lower dose settings.

9.2
Dose Optimization and Reduction in CT of Head and Neck Region

9.2.1
Dose Optimization and Reduction in Sinus CT

9.2.1.1
Introduction

Sinusitis is a frequent disorder. The underlying cause can be viral, bacterial, allergic, vasomotor or reactive. It can occur as a complication of dental infection or tooth extraction. In acute sinusitis there is generally no need for imaging, except when there is suspicion of complication with intra-orbital or intracranial extension. About one-third of the patients develop a chronic sinusitis. Chronic sinusitis is defined as persistent (acute) inflammation or frequently recurrent episodes of (sub) acute sinusitis. In these patients imaging is indicated as follows: to visualize the grade and extent of the inflammatory sinus pathology, to identify an eventual underlying cause, to describe the site of pathology in the complex anatomy of the maxillofacial region and to guide endoscopic surgery. Better understanding of the physiopathology of sinusitis and the development of functional endoscopic sinus surgery (FESS) have changed the role of imaging: CT has become the "gold standard" in the evaluation of (chronic) sinusitis, and has largely replaced conventional radiography, as CT is excellent for studying key regions of interest, such as the osteomeatal complex and anterior ethmoid region (Zinreich et al. 1996; Eggesbö 2006).

Before the advent of helical CT, direct coronal CT was the method of choice for visualizing sinuso-nasal anatomy. Since the introduction of helical and multidetector CT, axial imaging with fine (sub)millimetre collimation and reformations in the axial, coronal and sagittal plane with thin slices has become the method of choice, due to the possibility of getting an (nearly) isotropic volume data set. Coronal reformations give equal or even better image quality, due to the absence of dental filling artefacts, which were frequently present in earlier direct coronal scanning (Eggesbö 2006).

While CT is superior at demonstrating fine bony anatomy, the extent and anatomic localization of inflammatory lesions and complications such as sclerotic bone thickening and bone destruction, it has limitations in the differentiation of soft tissue masses, such as distinguishing mucosal thickening from pus-filled areas and inflammatory lesions (such as retention cysts, polyps and mucocoeles) from neoplastic processes. MR is superior at soft tissue characterization and has the advantage of using no radiation: MR is useful when in advanced opacification of the sinuso-nasal cavities a distinction has to be made between "simple" sinusitis, pyocele, fungal sinusitis and neoplastic disease. It is also excellent for visualizing invasion of the orbit or intracranial compartments. If neoplasm or complications of inflammatory processes are to be ruled out, additional imaging with intravenous administered gadolinium is mandatory (Rao and El-Noueam 1998).

9.2.1.2 Low-Dose CT of the Sinuses

Low-dose CT for sinuso-nasal imaging has been available for a long time and together with low-dose CT of the lung, introduced the application of low-dose CT to radiology. In 1991, before the introduction of helical CT, two studies had already stressed the ability to image the sinuses at a much lower dose than was commonly used in clinical practice at that time. Scanning a head phantom with a constant tube voltage at 120 kV, six successive sets of axial and coronal examinations were obtained, whereby the mAs setting was consistently reduced by approximately 50% every time (Marmolya et al. 1991): from 451 mAs to 16 mAs in the axial plane and from 503 mAs to 23 mAs in the coronal plane (dose reduction by a factor of 28). The same systematic dose reduction was used in a subsequent prospective study of 60 patients in the same way: divided into six groups of ten patients, each group underwent scanning with one of the six combinations of axial and coronal scanning as in the head phantom study. Additionally, 30 patients received the lowest mAs settings. In both the phantom and the patient study the amount of visually perceived noise increased, somewhat more in the axial than in the coronal plane, but all images were considered as of diagnostic image quality: "On the coronal images of the lowest setting of 23 mAs, the osteomeatal complex was clearly identifiable and presence of air versus soft tissue or fluid could be confidentially diagnosed" (Fig. 9.5). Another study of the same

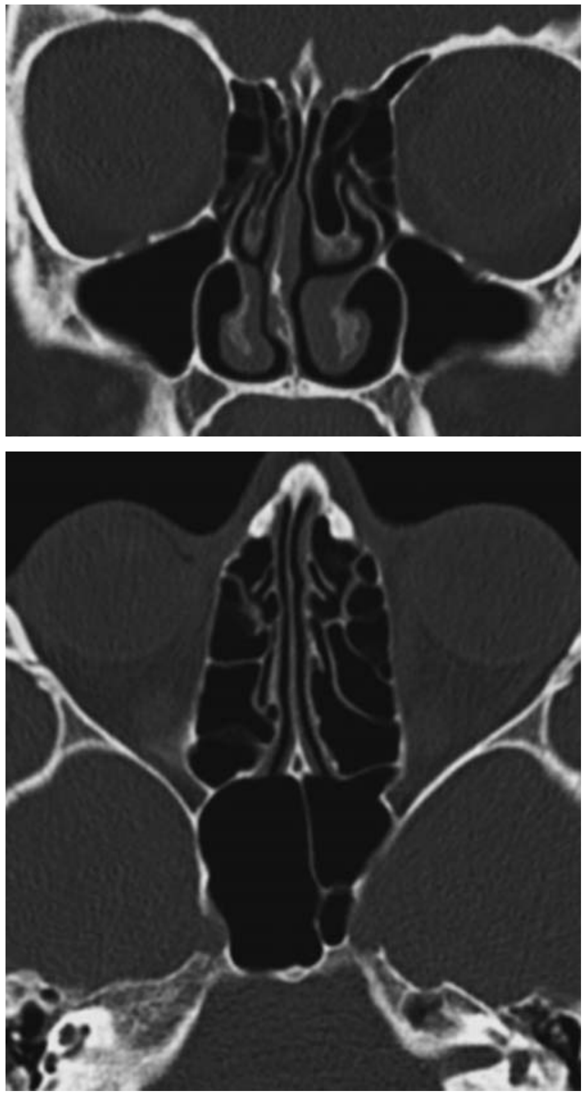
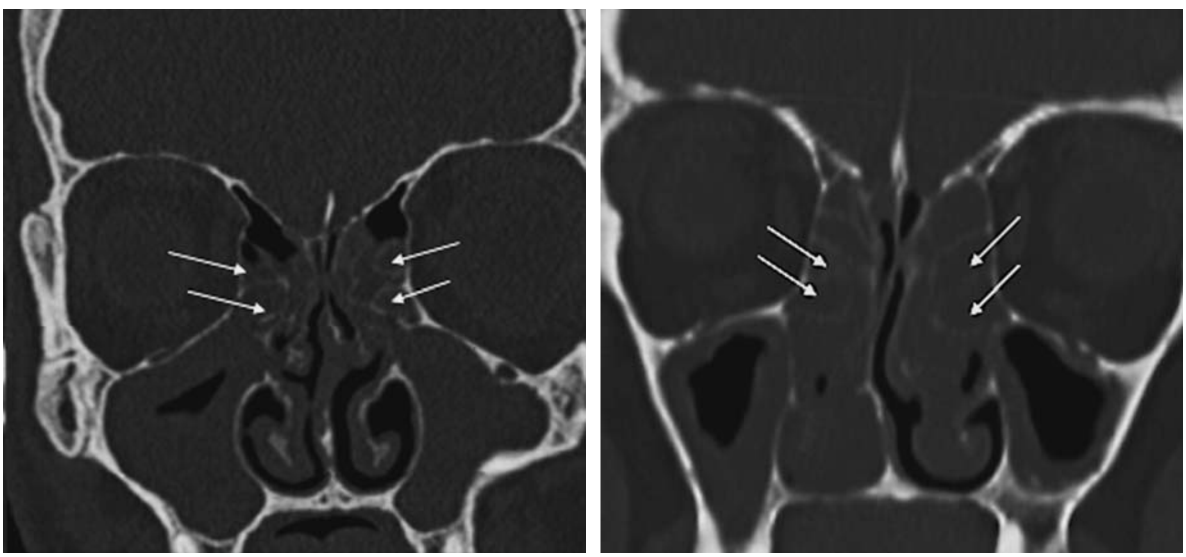

a
b

Fig. 9.5a, b. A 24-year-old woman with suspicion of chronic sinusitis. Low-dose 16-MDCT at 120 kV and 25 mAs ($CTDI_{vol}$ of 5.2 mGy) with 2 mm coronal (**a**) and axial (**b**) images show clearly the normal anatomy of the osteomeatal units and infundibulum with clear aeration of both maxillary, ethmoidal and sphenoidal sinuses. Calculated effective dose of CT exam is 0.10 mSv year recommended a comparable dose reduction: in 44 patients with inflammatory sinus disease, the dose was reduced by lowering the tube current from 390 mAs to 180 mAs, and further to 90 mAs and finally to 60 mAs (Duvoisin et al. 1991). In all cases the exact extent of the disease was correctly assessed on each of the low dose settings, with no false negatives: "although the less pleasant appearance to the eyes, the increased noise in the low dose images seemed not to induce errors of interpretation". They reported that in cases of extensive sinus disease the thickness and integrity of the fine bony (ethmoid) septa are sometimes difficult to evaluate on low-dose CT images (Fig. 9.6).

Several more recent studies confirmed these initial observations of the early 1990s: both with conventional incremental CT (Czechowski et al. 2001) and single-detector helical CT (Suojanen and Regan 1995; Kearny et al. 1997; Sohaib et al. 2001; Hein et al. 2002). They all proposed scan protocols with lower tube current settings of 40 or 50 mAs at 120 kV tube voltage as an alternative to many existing protocols which employed high mAs (up to 200 mAs – in the belief that this necessarily improves scan image quality). However, modern CT scanners are able to deliver excellent image quality at much lower dose levels (Kearny et al. 1997). Also the natural high contrast between the structures of interest (bone, air and soft tissue) in sinus CT enables using lower mAs settings and gives a correspondingly lower dose (Sohaib et al. 2001). The problem with these low-dose sinus CT studies is that they did not deliver additional dose descriptors, such as CTDI or effective dose, so that comparisons between different scanners is difficult: mAs values can vary by a factor of 2–3 for the same dose with different scanners. Therefore, directly comparing mAs values alone, across studies with different scanners, has limitations (Shrimpton et al. 1991).

Tack et al. (2003) calculated the effective dose of these previously reported low-dose CT studies of the sinuses (both incremental and single-detector helical CT studies), by using a commercially available software program on a PC (CT Expo, Hanover, Germany). For a mean scanned region of 12 cm length in their study they calculated a range of 0.11–0.24 mSv (mean: 0.17 mSv) for men and a range of 0.12–0.26 mSv (mean: 0.18 mSv) for women. In their own multidetector CT study, low-dose CT was compared with standard-dose CT on a 4-MDCT machine in the same 50 patients, who underwent both protocols. For standard-dose CT the scan protocol was 120 kV, 150 mAs, 4 × 1 mm collimation, pitch factor of 0.75, which gave a mean effective dose of 0.70 mSv for men and 0.76 mSv for women. For low-dose CT, 120 kV, 10 mAs, 4 × 1 mm collimation and a pitch



a b

Fig. 9.6a, b. In cases of extensive sinus disease it is difficult to evaluate the integrity of the fine bony (ethmoid) septa (*arrows*), especially at low-dose CT. This can be due to bony erosion, partial volume effect or lack of contrast at low dose. **a** Coronal 2 mm image of a low-dose 16-MDCT (same scan protocol as in Fig. 9.5) with effective dose of 0.12 mSv in a 56-year-old man; **b** comparable extensive sinus pathology in a 36-year old man at standard-dose 16-MDCT with 120 kV, 100 mAs, ($CTDI_{vol}$ of 21.4 mGy) and effective dose of 0.55 mSv, with bony erosion of the ethmoid septa (*arrows*) factor of 2 were used, which gave a mean effective dose of 0.047 mSv in men and 0.051 mSv in women, which is comparable with the radiation dose used in a four-view standard radiographic examination (Tack et al. 2003). They analysed mucosal abnormalities at eight different sinuso-nasal anatomic landmarks and two bony abnormalities and found greater variation in analysing cases of significant discrepancies in observations between three reviewers than between findings obtained at different dose levels: "in other words, observational variations associated with the decrease in radiation dose (by use of the low dose protocol) were fewer than those variations than can contributed to the reviewers themselves". They concluded that low-dose MDCT should be considered the imaging method of choice in the evaluation of chronic sinusitis.

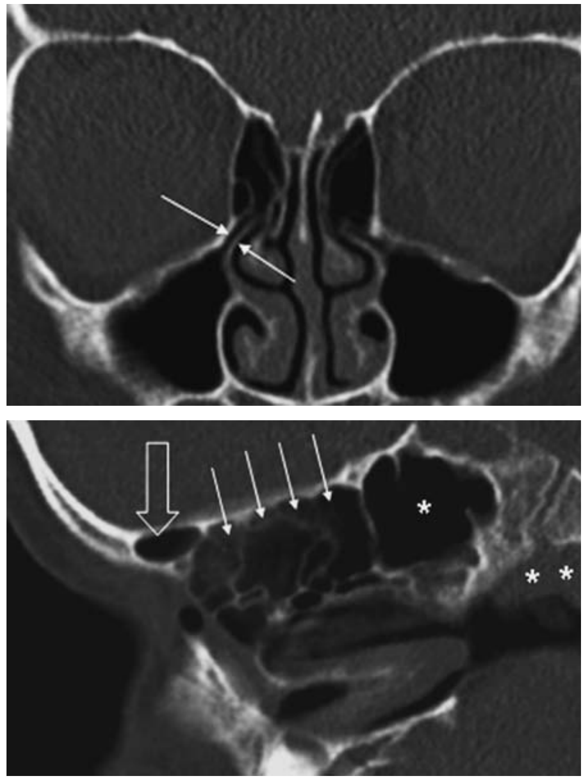
A local DRL study in our department of low-dose CT of the sinuses in 100 adult patients in 2005 gave a mean effective dose of 0.13 mSv and 0.15 mSv on two different MDCT machines, a 6-MDCT and 16-MDCT, respectively (unpublished data). For 6-MDCT ($n=50$), we used 80 kV, 60 mAs, 6 × 0.5 mm collimation, pitch factor of 1, which gives a $CTDI_{vol}$ of 5.04 mGy, and got a mean DLP of 54.8 mGy·cm. For the 16-MDCT ($n=50$), we used 120 kV, 25 mAs, 16 × 0.75 mm collimation, which gives a $CTDI_{vol}$ of 5.22 mGy, and got a mean DLP of 60.2 mGy·cm. In comparison with the scan protocols proposed by the manufacturer for scanning of the sinuses, this gives a dose reduction with a factor of 4: for the 6-MDCT they recommend the use of 130 kV, 70 mAs, 6 × 1 mm collimation with a pitch of 0.83, which gives a $CTDI_{vol}$ of 19.4 mGy; for the 16-MDCT they propose 120 kV, 100 mAs, 16 × 0.75 mm collimation, pitch of 0.55, which gives a $CTDI_{vol}$ of 21.3 mGy.

A recent study with a limited scan protocol of a non-contiguous incremental CT examination of the sinuses with ten 1-mm-thick coronal slices (interslice gap varied from 5 to 15 mm) at 120 kV and 40 mAs reached a very low mean effective dose of only 0.02 mSv, which is lower than the effective dose of standard radiography (Hagtvedt et al. 2003). Since this is only a limited exam in the coronal plane, small key anatomic landmarks with clinical importance might not have been able to be identified (Tack et al. 2003). Multidetector CT has the advantage of three-dimensional imaging, whereby all structures are better visualized in one of the three different anatomic planes: e.g. the spheno-ethmoidal recess is better visualized in the axial plane and the nasofrontal duct and periodontal spaces are better visualized in the sagittal plane.

Infections of the upper respiratory system are by far the most common cause of illness in infancy and childhood, accounting for approximately 50 percent of all illness in children younger than 5 years of age, and 30 percent in children between the ages of 6 and 12 years: the large majority of these upper respiratory infections are viral rhinitis or pharyngitis and are self-limiting diseases, also known as 'common cold'. About 10% of these upper respiratory infections are complicated by sinusitis, which a common problem in the paediatric population (George and Huges 1990). According to the American College of Radiology, acute sinusitis is a clinical diagnosis that may not need imaging (McAlister et al. 2000). Although the use of radiography is not indicated in these patients and should be discouraged, it is still frequently used for diagnosis: the physical examination alone can give difficulties in the diagnosis of acute bacterial sinusitis, because of the similarity of physical findings in the patient with uncomplicated viral rhinosinusitis. Also the clinical findings of recurrent or chronic sinusitis are often not specific, especially in younger children (Kronemer and McAlister 1997; McAlister et al. 2000). Plain radiography of the sinuses in children is technically demanding and difficult to perform, particularly in very young children, since correct positioning may be difficult to achieve. Therefore, the radiographic images may over- or underestimate the presence of abnormalities within the sinuses. Furthermore, the interpretation of sinus radiographs in children is difficult: there is a lack of accuracy (low specificity and sensitivity), largely related to the small size of the sinuses, the angulation of the X-ray beam and nasal secretions (Kronemer and McAlister 1997; McAlister et al. 2000).

The American Academy of Pediatrics (2001) therefore advises to reserve the use of imaging of sinusitis for situations in which the patient does not recover or worsens during the course of appropriate antimicrobial therapy or in cases of recurrent disease. The use of CT is restricted to children who have very persistent or recurrent sinus infections, who are not responsive to medical management and whereby surgery is considered an option as a management strategy and to those who present with complications of acute sinusitis. CT scan images give a much better detailed image of the sinus anatomy, and, when taken in conjunction with the clinical findings, remain a useful adjunct to guide (surgical) treatment.

Previous studies have already shown the lack of accuracy of sinus radiographs for the diagnosis of sinusitis in children in comparison with CT. In up to 75% of the patients the findings of the radiographs did not correlate with those on CT scans: in about 40% of the patients with normal radiographs, there were signs of pathology on CT scans and, vice versa, when there was an abnormality suspected on radiographs in 35% of the patients the CT scan showed normal findings (McAlister 1989). Another disadvantage of sinus radiographs is the great variability in their interpretation between radiologists: there is a low inter-observer agreement in the evaluation of these radiographs. This inter-observer agreement between radiologists is much better with CT (Kronemer and McAlister 1997; McAlister et al. 2000). However, there used to be an important threshold for use of CT in children for sinus evaluation: first of all, the radiation dose of CT is much higher than that of radiographs and, secondly, the use of sedation was frequently necessary (in young children) to perform a good CT exam. With the advent of spiral CT and MDCT, CT became the imaging modality of choice for the diagnosis of sinus disease in adults, whereby it is possible not only to lower the radiation dose, but also to shorten the examination time substantially. A recent study in 125 children showed that the effective dose of low-dose sinus MDCT can be lowered to a level of 0.05 mSv, which was comparable with the level of effective dose measured from standard radiographs in 69 other children (Mulkens et al. 2005a). In a scan protocol with 80 kV and with a mAs range of 15–25 mAs (according to age) on a 6- and 16-MDCT, a $CTDI_{vol}$ of 1.28 to 2.1 mGy was reached with preservation of diagnostic image quality (Fig. 9.7). Scan time was very short with a mean of 2.1 s and 9 s (16-and 6-MDCT, respectively), whereby there was no need for sedation for any CT exam. Compared to the "default" examination protocols for sinus CT in children as proposed by the manufacturer, the radiation using low-dose protocols, expressed in $CTDI_{vol}$, was 5–7 times lower. The large majority of the children (85%) were referred for CT for evaluation of chronic or recurrent sinus complaints (Fig. 9.8); only about 15% of the children were referred to CT for evaluation of an acute history with fever, sinus discomfort or headache or for evaluation of fever of unknown origin. This study shows another advantage of the use of low-dose CT in these children: CT permits the simultaneous visualization of the pharyngeal tonsils (adenoids), middle ear and mastoids, which are displayed in the same scan volume as the sinuses. In this way, CT displays the whole ear, nose and throat region in one examination, which is not possible with radiographs. The presence of adenoid hypertrophy and fluid in the middle ears ("glue ear") and mastoids (Fig. 9.8) is frequently seen in these children with recurrent upper respiratory infections and this can be accurately diagnosed at the same time with the same low dose (Mulkens et al 2005a).



a

b

Fig. 9.7a, b. Normal findings in low-dose CT exam of the sinuses in a 6-year-old girl (6-MDCT, $CTDI_{vol}$ of 1.68 mGy, effective dose of 0.035 mSv). **a** Coronal 2 mm image shows normal maxillary and ethmoidal sinuses with clear depiction of infundibulum, medially bordered by the uncinate process (*arrows*). **b** Sagittal 2 mm image shows normal frontal sinus (*open arrow*), ethmoidal cells (*small arrows*), sphenoid sinus (*asterisk*) and adenoids (*double asterisks*)

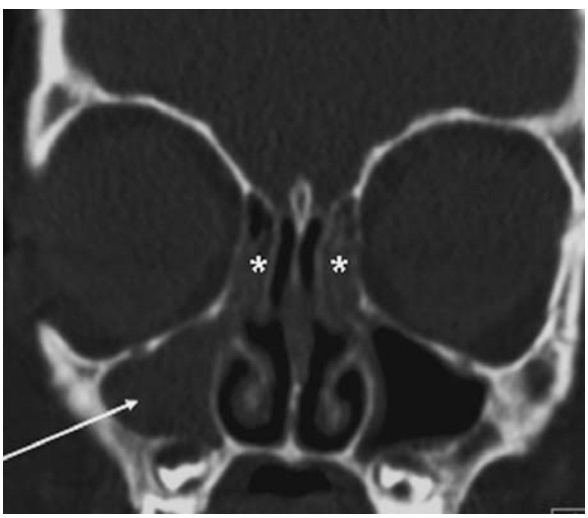
A disadvantage in imaging of sinusitis (both of adults and children) is the high incidence of soft tissue changes found in the sinus cavities in radiographic, CT and MRI exams in patients who undergo medical imaging for other reasons and who have no clinical evidence of sinus disease. This incidence is reported to be 33%–45% (Glasier et al. 1989; Gordts et al. 1997). A common cold or other upper airway infection acutely produces mucosal abnormalities in the sinuses in the majority of adults and children, and this is reflected in imaging, especially in patients who had a "cold" in the 2 weeks preceding imaging. Therefore, the diagnosis of acute and chronic or recurrent sinusitis should not be made on the imaging findings alone: the diagnosis of acute or chronic sinusitis should be made clinically, with confirmation with laboratory and imaging findings (Gordts et al. 1997; McAlister et al. 2000).

9.2.1.3 Conclusion

With modern multidetector CT, low-dose CT has become the method of choice to evaluate inflammatory pathology of the sinuses, especially in patients with chronic or recurrent sinusitis complaints. In patients with acute sinusitis, there is generally no need for imaging. Both in adults and children low-dose CT can be done with a mean effective dose that approaches or is comparable with the range of effective doses of standard radiography: 0.05–0.15 mSv. One has to keep in mind that with every imaging technique mucosal abnormalities in the sinus cavities are frequently found in patients referred for other reasons and who do not have clinical signs of sinus pathology. This lack of specificity, together with the lack of soft-tissue contrast, of low-dose CT is a disadvantage: when there is suspicion of complications of sinus disease with intra-orbital or intracranial extension (Fig. 9.9) or of underlying tumour pathology, the use of standard-dose CT with intravenous iodine contrast with additional soft window settings or MRI should be considered first.

9.2.2 Other Options for CT Dose Optimization in the Head and Neck Region

Since almost all other anatomical structures of interest in the head and neck region are soft tissues (pharynx and larynx, tongue and salivary glands, thyroid and parathyroid glands, muscles), the use of low-dose CT for imaging is not possible, since sufficient contrast (and dose) is necessary to distinguish between sometimes low-contrast lesions and normal soft tissue. Nevertheless, there are some options for optimizing the patient's dose and some specific indications whereby low-dose CT can be used.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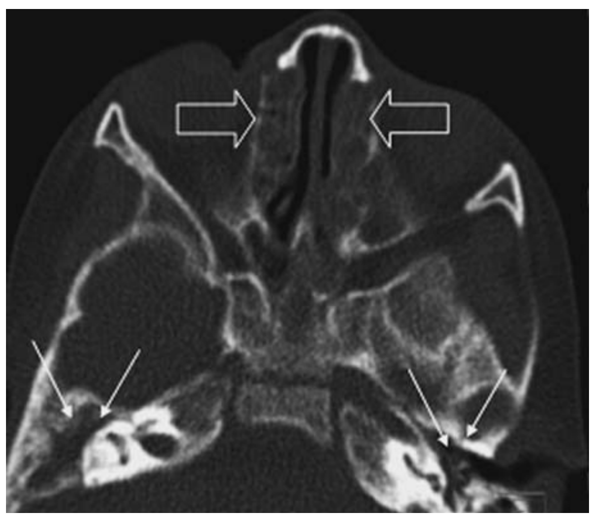
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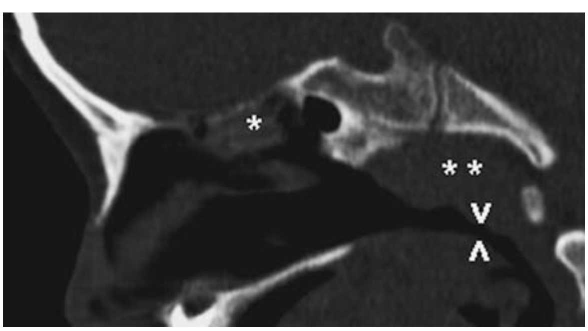
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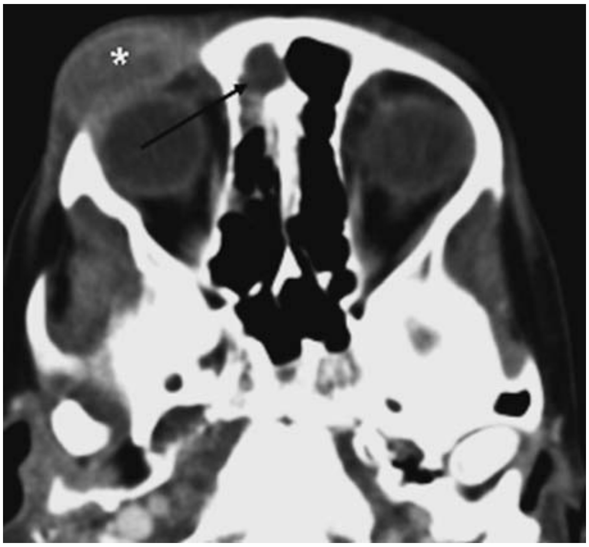
Fig. 9.8a–c. A 3-year-old girl with persistent upper airway infections, fever, cough and purulent nasal discharge. Low-dose 16-MDCT with $CTDI_{vol}$ of 1.43 mGy and effective dose of 0.036 mSv. **a** A 2 mm coronal image shows right maxillary (*arrow*) and bilateral ethmoidal sinusitis (*asterisks*). **b** Axial 2 mm image shows bilateral fluid (*arrows*) in the middle ear cavities, additionally. **c** Sagittal 2 mm image shows additionally adenoid hypertrophy (*double asterisks*) with narrowing of the nasal airway (*arrowheads*)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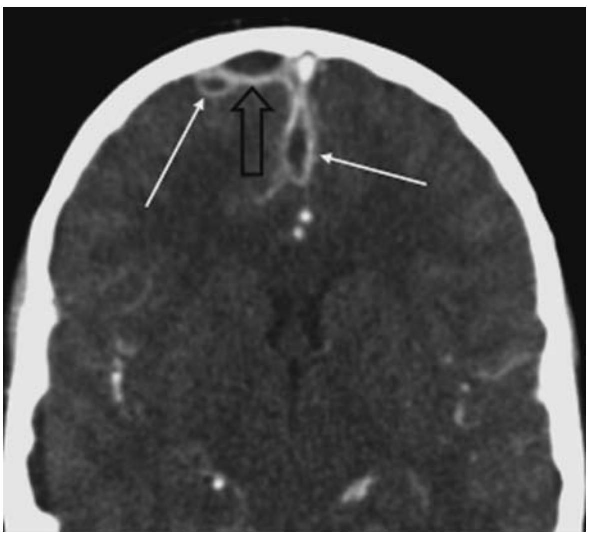
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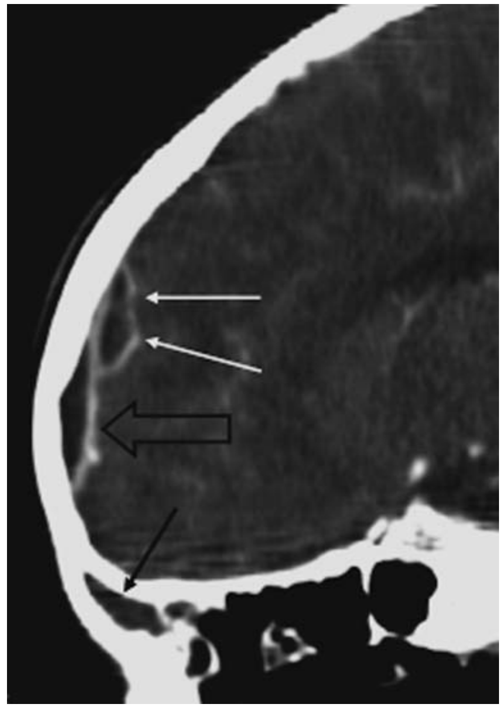
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Fig. 9.9a–c. A 10-year old boy with acute sinusitis develops peri-orbital swelling (cellulitis) and epilepsy. **a** Axial 5 mm image of standard-dose CT with intravenous iodine contrast with 120 kV and 125 mAs ($CTDI_{vol}$ of 24 mGy) shows right-sided frontal sinusitis (*black arrow*) and orbital cellulitis (*asterisk*). **b** There is intracranial extension with epidural (*open black arrow*) and subdural empyema collections (*white arrows*), which is confirmed on a 5 mm sagittal MPR image (**c**). Calculated effective dose of the CT exam was 1.4 mSv

The use of tube current modulation systems in modern multidetector CT have been shown to optimize and reduce a patient's dose with different ranges, depending on the body region examined (McCollough et al. 2006). Automatic tube current modulation in CT is analogous to the automatic exposure control or photo timing technique for automatically terminating radiographic exposure in conventional radiography, once the predetermined radiographic density has been obtained. Automatic tube current modulation in CT is based on the principle that X-ray attenuation and quantum image noise are determined by the size of the object and its tissue density. The tube current can thereby be adjusted (and reduced) with the changing regional attenuation during the continuous scanning process of helical CT, while maintaining image quality and increasing dose efficiency (Kalra et al. 2004). Modern modulation systems adjust tube current along the three different scan planes (angularly around the patient and along the long axis of the patient) constantly during the time of the scan process, and reach a substantial dose reduction with a range of 20% to more than 60%, depending on the anatomical region (Kalra et al. 2004; Mulkens et al. 2005b; McCollough et al. 2006). In the head and neck region, the use of tube current modulation has been shown to reduce the dose with a mean of 20%, both in adults (McCollough et al. 2006) and in children (Greess et al. 2004).

In dental radiology, CT is used in the preoperative planning of dental implant surgery, evaluating the bony anatomy of the mandibular and/or maxilla, measuring bone thickness and evaluating its integrity. Dedicated dental CT software packages are available to visualize the bone in parasagittal and "panoramic" reconstructions. Several studies have reported the possibility of reducing the dose for dental CT imaging, by reducing the tube current and increasing the pitch, both on single detector helical CT (Rustemeyer et al. 2004) and multidetector helical CT (Loubele et al. 2005). The dose can thereby be reduced by a factor of 8–9, with an effective dose in the range of 0.10–0.20 mSv, without sacrificing diagnostic image quality (Fig. 9.10): "the dose reduction with acceptable image quality was possible because only the bony anatomy is of interest for indications of maxillofacial surgery and dental implant planning, and not the contrast of the different soft tissues" (Loubele et al. 2005).

In analogy with low-dose CT of the abdomen for detection of urinary lithiasis, low-dose CT of the head and neck region can be used for detection of sialolithiasis, i.e. lithiasis of the salivary glands (Fig. 9.11).

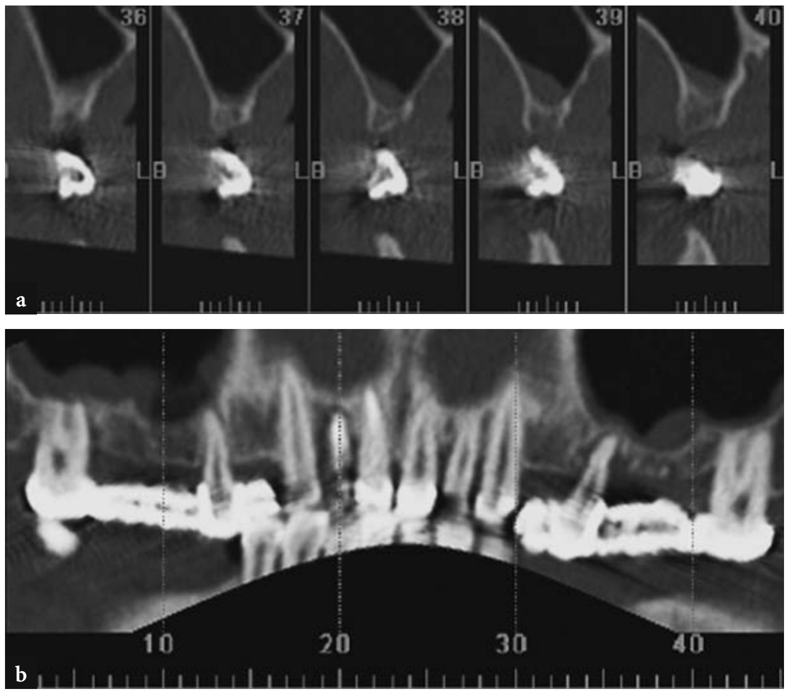

Fig. 9.10a, b. Low-dose dental CT exam for planning of dental implant surgery in a 38-year-old woman: 16-MDCT with 120 kV, 40 mAs and CTDI of 8.5 mGy. **a** Parasagittal 1.5-mm-thick reconstruction images and **b** "panoramic" 2-mm-thick reconstruction. Calculated effective dose of the CT exam was 0.11 mSv

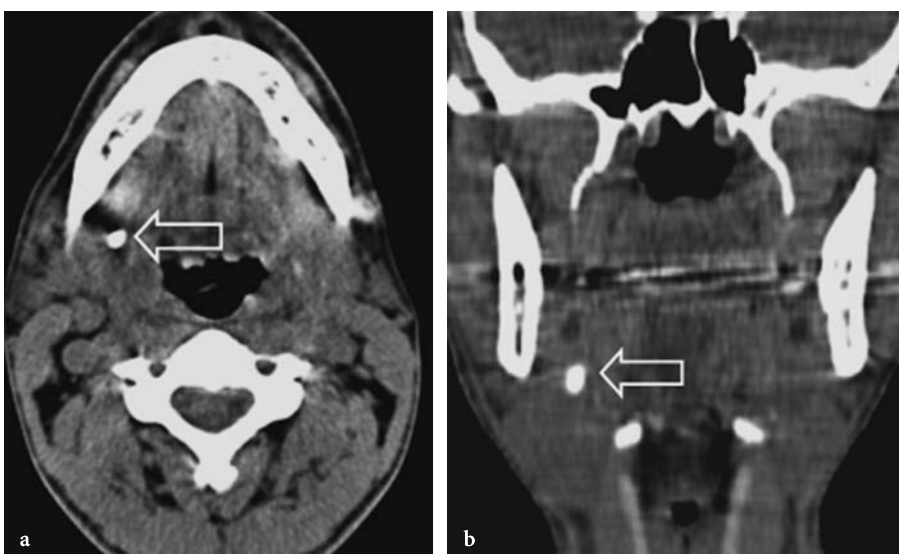

Fig. 9.11a, b. A 53-year-old man with pain and swelling of the right submandibular region during eating. Low-dose 6-MDCT with 110 kV, 50 mAs and $CTDI_{vol}$ of 4 mGy. **a** The 4 mm thick axial and **b** coronal images show large lithiasis (*open arrowhead*) at the junction of the gland with the ductus of Wharton. Calculated effective dose of the CT exam was 0.34 mSv

In this way the effective dose range was lowered from 1.5–2 mSv in our “standard” head and neck protocol to a range of 0.3–0.5 mSv by using both a lower kV (100 or 110 kV) and lower mAs (50 mAs) on both our 6- and 16-MDCT machines (unpublished data). We use the same low-dose MDCT protocol for preoperative planning of patients with thyroid surgery: to evaluate the size of the thyroid goitre, its contour and its relationship with the trachea, the great vessels and its extension in the upper mediastinum.

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