Radiation Dose Optimization in Pediatric Chest CT: Major Indicators of Dose Exposure in 1695 CT Scans over Seven Years

Optimierung der Strahlendosis in der Thorax-CT des Kindes: Einflussfaktoren der Strahlenexposition aus 1695 CT-Untersuchungen in sieben Jahren

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ABSTRACT
Purpose To analyze possible influencing factors on radiation exposure in pediatric chest CT using different approaches for radiation dose optimization and to determine major indicators for dose development.

Materials and Methods In this retrospective study at a clinic with maximum care facilities including pediatric radiology, 1695 chest CT examinations in 768 patients (median age: 10 years; range: 2 days to 17.9 years) were analyzed. Volume CT dose indices, effective dose, size-specific dose estimate, automatic dose modulation (AEC), and high-pitch protocols (pitch ≥ 3.0) were evaluated by univariate analysis. The image quality of low-dose examinations was compared to higher dose protocols by non-inferiority testing.

Results Median dose-specific values annually decreased by an average of 12%. High-pitch mode (n = 414) resulted in lower dose parameters (p < 0.001). In unenhanced CT, AEC delivered higher dose values compared to scans with fixed parameters (p < 0.001). In contrast-enhanced CT, the use of AEC yielded a
significantly lower radiation dose only in patients older than 16 years (p = 0.04). In the age group 6 to 15 years, the values were higher (p < 0.001). The diagnostic image quality of low-dose scans was non-inferior to high-dose scans (2.18 vs. 2.14).

**Conclusion** Radiation dose of chest CT was reduced without loss of image quality in the last decade. High-pitch scanning was an independent factor in this context. Dose reduction by AEC was limited and only relevant for older children.

**Key Points**
- The radiation dose of pediatric chest CT was reduced in the last decade.

**Materials and methods**
All CT examinations were performed in a single center with a board-certified division of pediatric radiology in the period from January 2007 to March 2014. The inclusion criterion was clinically indicated CT including the chest at the age of less than 18 years.

**Patient characteristics**
1695 CT examinations were performed in 768 patients (mean age ± standard deviation, 9.8 ± 5.6 years; median and 95% confidence level, 10.4 years [9.6; 10.1]; 1004 male (10.1 years ± 5.6; 10.4 years, [9.8; 10.5]) and 691 female (9.4 years ± 5.5; 10.2 years, [9.0; 9.8])). Based on the relation between children and body stature [21] and according to the diagnostic reference levels of the Federal Office for Radiation Protection [22], patients were divided into the following age groups: neonates (n = 16), ≥1 month and ≤1 year (infants; n = 195), 2–5 years (n = 285), 6–10 years (n = 405), 11–15 years (n = 531), 16–17 years (n = 263). Because of the small sample size, neonates were excluded from the subgroup analyses. The underlying indications for performing CT are listed in **Table 1**. As **Fig. 1** illustrates, the number of CT examinations did not change significantly in the observation time.

**CT devices**
Six different CT scanners (Siemens Healthcare GmbH, Forchheim, Germany; **Table 2**), each in line with the currently available CT generation, were used in our study, depending on the date of implementation in our institution (**Fig. 2**): Somatom Sensation 64 (05/2007 – 03/2014; 42% of all examinations), Somatom Definition Flash (09/2010 – 03/2014; 26%), Somatom Sensation Open (01/2007 – 09/2009; 23%), Somatom Definition (01/2007 – 05/2010; 7.5%), Somatom Definition AS+ (10/2009 – 07/2013; 1%), Somatom Sensation 16 (09/2008 – 04/2013; 0.5%).

**CT examination**
All procedures were in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. For this retrospective study formal consent was not required. All acquisitions were performed with specific pediatric CT protocols determined from the division of pediatric radiology. Scan parameters were adapted to patient body weight and age. The CT set-
Table 1 Indications for chest CT scans.

<table>
<thead>
<tr>
<th>Indication</th>
<th>Number (n)</th>
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<tbody>
<tr>
<td>infection process</td>
<td>852</td>
</tr>
<tr>
<td>monitoring of progress or response under therapy</td>
<td>239</td>
</tr>
<tr>
<td>non-malignant and non-infectious processes</td>
<td>205</td>
</tr>
<tr>
<td>cardiac and vascular imaging</td>
<td>149</td>
</tr>
<tr>
<td>staging</td>
<td>147</td>
</tr>
<tr>
<td>follow-up</td>
<td>40</td>
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<tr>
<td>trauma management</td>
<td>21</td>
</tr>
</tbody>
</table>

In 95% of all examinations, a slice thickness of 3 mm and an increment of 3 mm were applied. A slice thickness of 5 mm and an increment of 5 mm were chosen in only 5% of cases. For high-resolution (HR) images of the lung parenchyma, a high-resolution kernel (B60f) with a slice thickness of 1 mm and an increment of 5 mm was used. Further coronal and sagittal reformations were performed. The typical scan range was chosen from the jugular notch (fossa jugularis sternalis) as the cranial starting point and in the caudal direction including the adrenal glands as a landmark. The mean scan range was 22.9 cm, ranging from 8.6 – 33.6 cm.

Most examinations were performed with 100 kV (n = 1104; 65%) or 120 kV (n = 509; 30%). Less frequent kV values were 80 (n = 78; 4.5%) and 140 kV (n = 4; 0.5%). The patients scanned with 140 kV were among the age groups “11 – 15 years” and “16 – 17 years”. In these examinations angiography of the thoracic vessels was included, which may contribute to the relatively high dose parameters (effective mAs range: 122 to 128 mAs; CTDIvol range: 11 to 15 mGy). Most scans (n = 1259) were non-enhanced. Intravenous contrast agents were used in 436 acquisitions. The injected volume was adjusted to the patients’ body weight. 403 of them were primarily contrast-enhanced and 33 examinations included non-contrast and contrast-enhanced series. No iterative reconstruction algorithms were available during the observation time.

Radiation dose

Tube voltage (kV), volume CT dose index (CTDI; mGy) and dose length product (DLP; mGy·cm) were recorded for all CT acquisitions and extracted from the examination protocol.

In accordance with the European Guidelines on Quality Criteria for Multislice Computed Tomography, the effective radiation dose (Eeff; mSv) was calculated for all examinations by multiplying DLP with a conversion coefficient, depending on the body region scanned and the patient age (newborns 0.039; 1 year 0.026; 5 years 0.018; 10 years 0.013 mSv/(mGy·cm)) [23]. The CT scanners used in our study reported a CTDIvol referring to a 32-cm body phantom. However, for pediatric patients the conversion coefficient mentioned above refers to a 16-cm body phantom so that our DLP values had to be converted to a 16-cm phantom. For this purpose we used an additional scanner-specific conversion factor provided by the manufacturer (Table 3) to convert DLP to a...
16-cm phantom suitable for dose estimation in pediatric patients. However, even if the concept of E_{eff} has not been developed for patients and its applicability in children is indeed severely limited, it may serve as a rough estimation of the dose delivered.

In accordance with the American Association of Physicists in Medicine, size-specific dose estimates (SSDE; mGy) were calculated for all examinations [24]. Axial images were used to measure the widest transverse and anteroposterior skin-to-skin diameters of each patient and to determine the conversion factor.

To quantify the development of the dose descriptors (CTDI, SSDE, E_{eff}) within the observation time, linear regression was performed for each age group. Using the equations of the resulting lines, the percentage reduction in the CTDI, E_{eff} and SSDE per year was calculated. In addition, median dose parameters were compared between the starting year and the final year of our study for each age group.

### High-pitch protocols

The use of high pitch values was documented in our database. High-pitch protocols were only available on Somatom Definition Flash (Siemens Healthcare GmbH, Forchheim, Germany), which was established in 09/2010 in our institution. Thus, the evaluation of a potential impact of high-pitch protocols on dose estimates was limited to scans within this period (n = 944 scans in total).

### Dose modulation technique

Dose modulation technique was recorded if used. It was available during the entire observation period. Depending on the CT device, an automatic exposure control (AEC) algorithm (CARE Dose 4D) and, where available, an automatic tube voltage adjustment technique (CARE kV; both Siemens Healthcare GmbH, Forchheim, Germany) were used.
CARE Dose4D enables a user-specific adjustment of “image quality reference mAs” (mAsref) for each examination, depending on the required image quality. The parameter expresses the mAs applied on an average-sized phantom. However, the system also performs real-time mAs modulation for each rotation around the patient, depending on the attenuation profile. For this purpose, a single topogram was performed prior to each scan. Finally, the term of effective mAs (mAseff) takes the dependence on pitch factor into consideration and is defined as the quotient of mAs and pitch factor.

In addition, CARE kV adjusts the tube voltage (kV settings) suitable for the patient size and the chosen examination protocol. Tube current is then adapted automatically to maintain a constant contrast-to-noise ratio and to reach an appropriate combination of voltage and current [13]. The two techniques (CARE Dose4D and CARE kV) can be used simultaneously.

Diagnostic image quality
To assess the non-inferiority in diagnostic image quality of acquisitions with different radiation dose levels, non-enhanced and i. v. contrast-enhanced examinations (n = 20) with the highest and the lowest CTDI in each age group were analyzed. Image quality was assessed independently on a 3-point Likert scale (from 1 = lowest image quality to 3 = highest image quality) by three readers (one senior physicians with seven years of experience and two assistant physicians each with two years of experience) on a standard PACS workstation (Centricity RA 1000, GE Healthcare, Waukesha, Wisconsin, USA). In non-enhanced scans, the pulmonary intersegmental septum of the lower lobe, subsegmental pulmonary arteries and bronchi, as well as motion and breathing artifacts were evaluated. In enhanced scans coronary arteries and sinus, the aortic valve and pulsation artifacts were assessed additionally. Readers were blinded to all identifying data and technical details.

Statistical analysis
For statistical analysis, IBM SPSS Statistics (version 22 for Windows, Ehningen, Germany) and (SAS jmp, version 11.1.1 for Windows, SAS Institute Inc., Cary, NC, USA) were used.

For all statistical tests, a significance level of p < 0.05 was set. Continuous variable data are presented as means ± standard deviations. Data that did not follow a normal distribution are presented as median with 95% confidence interval (CI). By using univariate multifactorial analysis of variance, the influence of age, sex, CT scanner, pitch factor and dose modulation on dose descriptors was evaluated.

A non-inferiority analysis was performed for the 3-point image quality score using a 95% confidence interval [25]. A non-inferiority margin of 0.2 image quality score points for the difference between the examinations was predefined. To evaluate inter-rater reliability, a two-way intraclass correlation coefficient (ICC) was calculated.

Results
Radiation dose
Dose descriptors depend on patient age; see the appendix for detailed numerical information about the dose values. ► Fig. 2 demonstrates that the median dose-specific values generally decreased within the observation time. Especially between the years 2009 and 2010, a major leap can be observed. In the period from 2011 to 2013 only minor differences can be found. In addition, ► Fig. 3 confirms the dose reduction in all age groups. Following linear regression, dose parameters dropped by an average of 12% per year in the age groups ≤ 1 year, 2 – 5 years, 6 – 10 years and 11 – 15 years. Only in the age group “16 – 17 years” was a minor annual decrease of 10% observed. Comparing the median dose values from the starting year 2007 to the final year of our study reveals a percentage decrease of 74% in the age group ≤ 1 year and a reduction of 90%, 76%, 82% and 82% in the following age groups.

High-pitch protocols
In the period from 09/2010 to 03/2014, 414 of 944 examinations were performed with high pitch values (≥ 3.0) on Somatom Definition Flash. ► Fig. 4 illustrates the distribution of dose descriptors in the different age groups. All indicators showed lower values when high-pitch protocols were used, independent of contrast agent use. When age, sex, and the use of AEC were included in univariate analysis, these differences between acquisitions with and without high-pitch mode were statistically significant (p < 0.05).

| Table 3 | Scanner-specific conversion factors from DLP Ø 32 cm to DLP Ø 16 cm.
| Tab. 3 | Scanner-spezifische Konversionsfaktoren von DLP Ø 32 cm auf DLP Ø 16 cm.

<table>
<thead>
<tr>
<th>pediatric body</th>
<th>somatom sensation 16</th>
<th>somatom definition AS†</th>
<th>somatom definition</th>
<th>somatom definition flash</th>
<th>somatom sensation open</th>
<th>somatom sensation 64</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 kV</td>
<td>n. a.</td>
<td>2.5</td>
<td>2.3</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>100 kV</td>
<td>2.0</td>
<td>2.4</td>
<td>2.4</td>
<td>2.1</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>120 kV</td>
<td>2.0</td>
<td>2.3</td>
<td>2.3</td>
<td>2.1</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>140 kV</td>
<td>n. a.</td>
<td>n. a.</td>
<td>n. a.</td>
<td>2.2</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

DLP = Dose length product; Dosislängenprodukt.
Dose modulation

A dose modulation technique was used in 409 of all 1695 examinations. These scans were performed with a median effective mAs of 74 mAs [95% CI, 77; 85]. 80 kV were chosen in 39 cases, 100 kV in 161 scans and 120 kV in 206 scans. Three patients were scanned with 140 kV (Methods and materials, CT examination). These parameters accounted for a median CTDI of 4.3 mGy [95% CI, 5.2; 6.0], a median Eeff of 4.1 mSv [95% CI, 5.1; 6.0] and a median SSDE of 7.2 mGy [95% CI, 8.2; 9.4].

In non-enhanced acquisitions dose parameters were higher in all age groups when AEC was used compared to a manual adjustment of the examination protocol (Fig. 5). These differences were statistically significant in the age groups 6–10 years, 11–15 years and 16–17 years (p < 0.001) – even when sex and the use of different CT devices was taken into account – and not statistically significant in the age groups ≤ 1 year and 2–5 years (p = 0.08 – 0.70).

In 298 of 436 contrast-enhanced chest CTs, AEC was carried out. The age groups ≤ 1 year and 16–17 years showed a lower median CTDI, Eeff and SSDE when AEC was applied. However, only in the age group “16–17 years” was the difference statistically significant (p = 0.04; age group ≤ 1 year, p = 0.5) (Fig. 5). The median values of age groups 2–5 years, 6–10 years and 11–15 years presented higher dose parameters in scans with dose modulation. For the two older age groups, these differences were statistically significant (p < 0.001; age group “2–5 years”, p = 0.2).

Image quality

The mean image quality scores were 2.18 [95% CI, 2.04; 2.32] in the subgroup with the highest CTDI values and 2.14 [95% CI, 1.98; 2.30] in acquisitions with the lowest radiation dose. Thus, differences in image quality between the examinations with the highest and lowest CTDI values resided within the predefined non-inferiority margin (Fig. 6). The overall inter-rater reliability was found to be ICC 0.889, (95% CI: 0.784, 0.950; p < 0.001), indicating almost perfect agreement.

Discussion

In our retrospective observational study over a period of seven years, a significant reduction in radiation dose in pediatric chest CT was observed without a loss of diagnostic image quality using state-of-the-art scanners and dose optimization strategies. In particular, the implementation of high-pitch scanning seems to essentially contribute to this development. Interestingly in this context, the different AEC methods provided were not as efficient as expected. In an early patient study dose values were reduced by an average of 38% when using tube current modulation [14].

CT scanners and software equipment evolved as decisive influencing factors of CT radiation dose [19]. Meanwhile the focus shifted from high-quality CT imaging with precise anatomic information to better manage radiation dose and to maintain a diagnostic image quality related to the clinical question. However, this fact should be further addressed in national and international guidelines for radiation protection. During the process of accepting noisier images without reducing diagnostic capabilities, pediatric imaging has adopted a pioneering role [7]. Even with regard to adult CT, a maximum of image quality is rarely required to answer the clinical question.

Comparing our dose parameters (Appendix) to a national survey from 2007 that proposed reference dose values in pediatric CT for each age group, we found that in the initial year of the observation time (2007) the median CTDI in our study was at the upper limit of the corresponding reference values [26], for example in children aged 2–5 with a median CTDI of 5.4 mGy and a reference value of 5.5 mGy. In this period, the CTDI exceeded the reference level in the age group of infants with only four patients (≤ 1 month and ≤ 1 year; median CTDI, 4.3 mGy; reference value 3.5 mGy). However, the CTDI was clearly below the reference levels in the following years across all age groups, also compared to the latest announcement of the Federal Office for Radiation Protection (BfS) [27]. Especially in the last years of the observation time (2013 and 2014), the CTDI was more than three times lower than the corresponding reference value in some age groups, for example in children aged 11–15 with a median CTDI of 1.8 mGy (reference value, 6.5 mGy) matching a range of low-dose imaging.

Migliorelli et al. reported mean radiation doses of 744 scans performed between 2001 and 2011 that were more than twice as high as in our study, when comparing the corresponding age groups [1]. It can be supposed that different local guidelines for radiation protection and the technical developments made since the ending of this previous study account for the differences in dose estimation. However, it has to be considered that iterative reconstruction was not applied in our study and its use may have led to a further dose reduction [16].
The implementation of dual-source CT devices allowed for high-pitch scanning, which has been applied to pediatric chest and cardiac CT to reduce motion artifacts [7]. Our data included a significant decline in median dose values from 2009 to 2010, when Siemens Somatom Definition Flash (Siemens Healthcare GmbH, Forchheim, Germany) with the possibility of high-pitch protocols was implemented. Providing a large patient population, the method appears recommendable in all age groups and independent of contrast agent use. In addition, further settings of the scanner may have contributed to dose reduction: In contrast to the other CT devices in our study, Somatom Definition Flash has two detectors combining the photodiode and an analog-to-digital converter, which may reduce electronic noise, especially in lower dose applications (Table 2). In smaller patient populations and compared to our patient cohort – restricted age groups, favorable radiation doses have been reported with the high-pitch technique for pediatric chest CT imaging and CT angiography (CTA) [18, 28, 29]. In addition, several previous studies have suggested that high-pitch scanning does not compromise image quality, which seems reasonable in light of our results [28, 29].

Our data demonstrate that the use of a dose modulation technique was not always advantageous and should be considered individually. Karmazyn et al. found that in abdominal CT with AEC, dose reduction was least effective for body weight less than 20 kg (our age groups 1–3, considering Child Growth Standards of the World Health Organization, WHO) [30, 31]. The vast majority of children from ages 2–15 received higher radiation exposure when AEC was used in contrast-enhanced chest CT. However, adolescents (16 and 17 years) seem to benefit from dose modulation, which agrees with Karmazyn’s statement about the highest effectiveness of AEC at a body weight range over 60 kg [30]. However, according to our results, dose modulation is applicable in infants, which contradicts the previous findings. One of the reasons for this phenomenon could be that manual adjustment is hampered in the youngest and oldest age groups, so that the stored algorithms of AEC achieve comparatively favorable dose parameters. In infants a relatively low patient number and little experience with manual adaption in the early years of the study can be considered as possible reasons. However, the oldest age group presents a rather heterogeneous patient cohort concerning weight and body diameter, so that fluctuating dose values may occur. Our results are important because radiologists should not only take patient size but also the use of contrast agent into account when considering pediatric chest CT with dose modulation.

The use of dose modulation systems includes potential sources of error, which may explain the heterogeneous data in the litera-

**Fig. 4** Dose parameters depending on the application of high-pitch mode. Median volume CT dose index (CTDI; mGy), effective dose (Eeff, mSv) and size-specific dose estimate (SSDE; mGy) in the different age groups depending on the application of high-pitch mode (Y = yes, N = no) and contrast agent use (left, non-enhanced; right CM = contrast agent). This figure is limited to scans in the period from 09/2010 to 03/2014 (n = 944).

**Abb. 4** Dosiswerte in Abhängigkeit von Verwendung des High-pitch-Modus. Medianwerte für Volumen-CT-Dosisindex (CTDI; mGy), effektive Dosis (Eeff, mSv) und size-specific dose estimate (SSDE; mGy) in den verschiedenen Altersgruppen in Abhängigkeit der Verwendung des High-Pitch-Modus (Y = ja, N = nein) und einer Kontrastmittelapplikation (links, nativ; rechts, kontrastangehoben). Die Abbildung beschränkt sich auf die Untersuchungen in der Zeitspanne von 09/2010 bis 03/2014 (n = 944).
ture and the unfavorable dose parameters in our study. A possible technical problem refers to an inappropriate configuration of the scanner for the use of AEC with different patient sizes. In this context, we suspect that the expertise of the manufacturer and our experience with AEC protocol utilization were limited in the early years of our study. At that time, it is possible that inappropriately high reference mAs values were selected, which may partly explain the elevated dose values and provides some potential for further optimization. After AEC protocols were adopted from the manufacturer initially, they have been adjusted in the following years with increasing know-how and growing feedback to the manufacturer. In addition, patient movement between the localizer and subsequent scans may lead to application of an inappropriately adjusted tube current profile. Finally, an inaccurate position on the CT table and insufficient centering of the patient may be relevant in younger children [32]. In this context, manual adjustment should be considered as a reasonable alternative to AEC, at least in dedicated pediatric centers with the necessary pediatric CT experience. Further development on this issue for the pediatric population is recommended.

Some aspects of our study may seem obvious. Nevertheless such a calculation of dose values and analysis of the dose development in the context of the clinical routine process have not yet been published to the best of our knowledge. As low kV protocols and iterative reconstruction are not universally included in pediatric CT today, the results of our study still seem relevant for a majority of pediatric examinations worldwide.

Our study has the following limitations: The study was set up at a single center; consequently it depends on the local standard of care and the on-site technical installations, for example CT devices of only a single manufacturer were used. Additionally, due to the lack of availability, iterative reconstruction algorithms and low kV protocols were not included.

In summary, radiation dose in pediatric chest CT has been considerably reduced in the last decade without a relevant loss of image quality. High-pitch scanning appears to be an effective method of dose optimization whenever iterative reconstruction is not available. However, in our institution the use of dose modulation techniques had to be considered individually according to patient size and depending on the examination protocol. In this context, a centralized position of the patient on the CT table is of basic importance for reliable dose adjustment. Moreover, additional options are available today to tap the further potential of dose reduction, for example iterative reconstruction.
The authors declare that they have no conflict of interest.

References


CLINICAL RELEVANCE

- High-pitch protocols should be used for pediatric chest CT.
- Acquisitions with fixed parameters should be considered as an alternative to AEC.
- The use of AEC may be advantageous in adolescents.

ABBREVIATIONS

<table>
<thead>
<tr>
<th>AEC</th>
<th>Automatic Exposure Control</th>
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<tbody>
<tr>
<td>CI</td>
<td>Confidence Interval</td>
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<tr>
<td>CT</td>
<td>Computed Tomography</td>
</tr>
<tr>
<td>CTA</td>
<td>Computed Tomography Angiography</td>
</tr>
<tr>
<td>CTDI</td>
<td>Volume CT Dose Index</td>
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<tr>
<td>DLP</td>
<td>Dose Length Product</td>
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<tr>
<td>Eeff</td>
<td>Effective Radiation Dose</td>
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<tr>
<td>ICC</td>
<td>Intraclass Correlation Coefficient</td>
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<tr>
<td>IV</td>
<td>Intravenous</td>
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<tr>
<td>SSDE</td>
<td>Size-Specific Dose Estimate</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
</tbody>
</table>
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[27] Federal Office for Radiation Protection (BfS). Publication of updated diagnostic reference levels for diagnostic and interventional X-ray examinations. 2016.;44,Tab. 8


