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Challenges to Protocol Optimization Due to Unexpected Variation of CT Contrast Dose Amount and Flow

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Abstract High-quality computed tomography (CT) exams are critical to maximizing radiologist's interpretive ability. Exam quality in part depends on proper contrast administration. We examined injector data from consecutive abdominal and pelvic CT exams to analyze variation in contrast administration. Discrepancies between intended IV contrast dose and flow rate with the actual administered contrast dose and measured flow rate were common. In particular, delivered contrast dose discrepancies of at least 10% occurred in 13% of exams while discrepancies in flow rate of at least 10% occurred in 42% of exams. Injector logs are useful for assessing and tracking this type of variability which may confound contrast administration optimization and standardization efforts.

Keywords Computed tomography · Computer communication networks · Computer hardware · Contrast media · Diagnostic image quality

Introduction

In computed tomography (CT), there are many factors contributing to the overall quality of the exam: patient anatomy and physiology, acquisition settings, and contrast administration [1–7]. Patient-related factors such as cardiac output, intravascular volume, patient weight, patient height, renal function, and concurrent comorbidities are known to affect contrast enhancement timing, with the most important factors being patient weight, cardiac output, and intravascular volume affecting arterial enhancement [3, 8, 9]. Acquisition parameters including mA, kVp, noise index, bolus tracking technique, and reconstruction algorithms have a significant effect on study quality and have been studied extensively [2, 3, 7, 8, 10]. Radiation reduction techniques, including low-dose protocols and new reconstruction algorithms, have garnered the most recent attention due to the inherent and sometimes unknown exposure risks [10, 11]. Most evaluation to date regarding contrast administration has been centered on contrast timing using manual delays, a test bolus, or bolus tracking technology [8, 9, 12, 13]. Although static contrast volume and flow rates based on patient weight have traditionally been used, recently there has been more interest in looking at individualized patient protocols to take into account patient physiology which achieves more consistent organ enhancement, decrease overall iodine dose, and reduce costs [5, 7, 9].

The volume and delivery rate of intravenous contrast are important factors affecting the quality of computed tomography (CT) images and represent a trade-off with patient safety [14]. Currently the amount of contrast given to a patient is assumed to be the protocol amount. There are several reasons why the actual amount of contrast delivered to a patient could differ from the amount specified in the scan protocol of the organization. These include venous access, contrast extravasation, injector malfunction, and incorrect injector calibration. Studies that compare the degree of organ enhancement achieved with the amount of contrast delivered based on the protocol could thus be flawed as the actual amount delivered has previously been difficult to capture. [9] Recent availability of commercially available informatics devices that automatically capture the specifics of the contrast injection for each patient now enables the evaluation of the actual volumes and flow rates of contrast that each patient receives. We hypothesized that a fair number of routine patient CT exams do not receive the prescribed amount

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of intravenous contrast, which can affect the diagnostic acceptability of the scan. The purpose of this study was to use automatically acquired contrast administration data to determine the frequency of abdominal pelvic CT exams where the actual amount of the contrast delivered to the patient was different from what the scan protocol specified. To our knowledge, the variability of what the volume and rate of contrast administration patient's actually receive has not been assessed. Logs from three MEDRAD power injectors were extracted to study the patterns in contrast delivery compared with the prescribed parameters and to determine the magnitude and frequency of deviations.

Methods

The University of Washington Medical Center (UWMC) has three multi-detector CT suites, each equipped with a power injector containing a new software interface that automatically captures the contrast injection profiles of each patient.

Contrast injection profiles from consecutive patients undergoing single-phase contrast-enhanced abdominal and pelvic CT at any of the three UWMC scanners between October 26, 2010 and March 21, 2011 were retrieved using a commercially available informatics platform (Certegra Manage.Report, Medrad Inc., Indianola, PA). The data captured for each injection include procedure type, patient date of birth, patient gender, contrast concentration, contrast loaded, saline loaded, contrast delivered, saline delivered, peak flow A (contrast), peak flow B (saline), peak pressure A (contrast), peak pressure B (saline), protocol name, and atypical events. For this study, the protocol contrast volume and injection rate, the amount of contrast that was loaded into the injector, and the volume and peak flow rate of the amount of contrast that was actually delivered to each patient were entered into a database for comparative analysis. All exams were performed on 64 channel CT platforms (GE Healthcare) and consisted of single venous phase scans of the chest–abdomen–pelvis or abdomen–pelvis. Typical parameters were 64×0.625-mm collimation, pitch 1.375, xyz-tube current modulation with a NI of 30 (AutoSmart mA, GE Healthcare), and tube current selected based on scan field-of-view (100 kVp if sfov <34 cm; 120 kVp if >34 cm). For these exams, a weight-based contrast bolus protocol was used at a fixed injection duration of 40 s; due to the fact that the patient weights were not recorded by the Medrad server, individual injection profiles were placed in each category based on the proximity of the delivered contrast to the prescribed protocol amount (Table 1). Contrast (Iohexol 350, GE Healthcare) was injected with a dual-head programmable power injector (Stellant D, Medrad Inc). Our university human subjects institutional review board approved this HIPAA compliant study; and the requirement for written informed consent was waived due to the retrospective study design.

Table 1 Prescribed contrast volume and rate as a function of patient weight

Low (delivered ml)	High (delivered ml)	Prescribed volume (ml)	Prescribed rate (ml/s)	Weight (lbs.)
0	89	88	2.2	≤120
89	115	96	2.4	121–143
115	124	121	3.0	144–187
124	163	145	3.6	188–210
163	170	168	4.2	211–250
170	999	186	4.6	>250

Low and high values were chosen as the inclusive and exclusive values of the delivered contrast amount for each category

During data analysis, autocorrelation plots were used to check for the presence of serial correlation between observations for the same scanner. Distributions of measurements from each scanner were compared using Kolmogorov–Smirnov tests to determine if the scanners could be grouped.

Throughout, continuous variables are summarized as median [inter-quartile range] and the range. Medians were compared with 0 using the sign test. Continuous variables were compared between groups using the Mann–Whitney U test.

Results

A total of 1,366 observations from the three scanners (289 from CT1, 311 from CT2, and 766 from CT3) were collected. Fifty-eight observations were indicated to be abnormal terminations per the Medrad server log and were excluded (12, 12, and 34, from each CT scanner, respectively). Lastly, three gross outliers, which were not indicated as abnormal terminations per the log, were detected by visual inspection and excluded as they suggested abnormal termination. This resulted in a total of 1305 observations (276, 297, and 731, respectively) available for analysis.

The series of percent differences between delivered and prescribed contrast volumes (%ΔD) and percent differences between peak and prescribed flow rates (%ΔR) were evaluated. Inspection of autocorrelation plots revealed no significant serial correlation, so observations were treated as independent. Additionally, observations from all three scanners were pooled for subsequent analyses as pairwise Kolmogorov–Smirnov tests did not indicate important differences in distributions of %ΔD and %ΔR. %ΔD ranged from −13.9 to 25.0 % with a median [IQR] of −0.16 % [−0.31, −0.02] (p<0.001 for median=0) while %ΔR ranged

Table 2 Frequency of scans with differences between delivered and prescribed contrast volume and flow rates

	N (%) for %Δ*D* within each range						Totals	
	1–5 %	5–10 %	10–15 %	15–20 %	20–30 %	> 30 %	> 5 %	> 10 %
Positive differences	46 (3.5)	48 (3.7)	43 (3.3)	58 (4.4)	58 (4.4)	0 (0.0)	207 (15.9)	159 (12.2)
Negative differences	32 (2.4)	9 (0.7)	5 (0.4)	0 (0.0)	0 (0.0)	0 (0.0)	14 (1.1)	5 (0.4)
P value	0.141	<0.001	<0.001	<0.001	<0.001	–	<0.001	<0.001
	N (%) for %Δ*R* within each range						Totals	
Positive differences	490 (37.5)	213 (16.3)	58 (4.4)	46 (3.5)	72 (5.5)	62 (4.8)	451 (34.6)	238 (18.2)
Negative differences	12 (0.9)	25 (1.9)	69 (5.3)	6 (0.5)	82 (6.3)	151 (11.6)	333 (25.5)	308 (23.6)
P value	<0.001	<0.001	0.375	<0.001	0.468	<0.001	<0.001	0.003

Lower bounds are exclusive and upper bounds are inclusive. Percentages are out of 1,305 observations. *P* values correspond to tests of equal frequencies of positive and negative differences within a given range

%ΔD percent differences between delivered and prescribed contrast volumes, *%ΔR* percent differences between peak and prescribed flow rates

from −70.8 to 92.7 % with a median [IQR] of 4.7 % [−6.1, 5.8] ($p<0.001$ for median=0).

While the median %Δ*D* was significantly less than 0, the magnitudes of the positive differences were significantly larger than the magnitudes of the negative differences (median [IQR]: 12.2 % [4.0, 18.9] vs. −0.2 % [−0.4, −0.1], $p<0.001$) (Table 2). In particular, 15.9 % of the differences were positive and greater than 5 % in magnitude compared with the 1.1 % which were negative and also greater than 5 % in magnitude. Similarly, 12.2 % of the differences were positive and greater than 10 % in magnitude compared with the 0.4 % which were negative and also greater than 10 % in magnitude. By contrast, while positive %Δ*R* differences were significantly more common than negative differences at 72.5 % ($p<0.001$), the magnitudes of the positive %Δ*R* differences were significantly smaller than the negative differences (median [IQR], −28.6 % [−41.7, −12.8] vs. 5.0 % [4.7, 10.0], $p<0.001$; Table 2).

Discussion

The total amount of contrast to a patient can affect the degree of organ enhancement [2, 3, 7, 13], while changes in the flow rate can affect the magnitude and timing of peak vascular enhancement [2, 3]. The results of this study revealed 12.2 % of administrations from a large data base deviated from the prescribed amounts by more than 10 % and that 97 % of these deviations involved delivering too much contrast rather than too little based on the protocol. Furthermore, 8.8 % of positive deviations were between 15 and 30 %, while no deviations greater than 30 % were observed. While not studied here, some of these deviations may correspond to increased risk to the patient [14].

In our database, the peak flow rate was found to be within 1 % of the prescribed rate only 1.5 % of the time, while it exceeded the prescribed amount by 1–5 % in 37.5 % of administrations and 5–10 % in 16.3 % of administrations. However, the peak flow rate was 20–70 % below the prescribed rate in 17.9 % of administrations. Contrast flow rate has been seen to have a large effect on study quality as it changes the timing of contrast enhancement [2, 3]. Limiting this variable as much as possible would allow for more consistent phases of enhancement, especially during multiphase exams [7].

The high rate of variability between prescribed and received intravenous contrast volumes and rates warrants further study to determine the causes of this variability; particularly if causes of this variability are correctable. An important assessment of this deviation is whether or not this had an adverse effect on the study quality, which was not the focus of this project. One advantage of this new contrast data log is that it can be continually mined and compared with study parameters including parenchymal enhancement, iodine dose delivered, and complication rate for continual quality control.

Many factors contribute to the overall quality of a CT study, but only a limited number can be altered. Some factors which are not adjustable can be accounted for instead, such as patient anatomy and physiology which can vary drastically between patients and have a large effect on scan quality [1, 2]. Optimization and standardization of the contrast rate and volume are keys to acquiring high quality CT studies with little variability between patients. High-quality techniques allow the radiologist to consistently see studies that are the same in quality and characteristics outside of the patient's normal anatomic and physiologic differences. In theory, this may help to reduce interpretive error due to study variation based on incorrect contrast usage although this has not been formally evaluated.

One limitation is that only the loaded amount of contrast and not the prescribed contrast volume of the scan protocol are captured by the MEDRAD injectors. Thus the prescribed amount of contrast was estimated based on the delivered contrast volume. However, this would tend to underestimate some

deviations if the delivered contrast was too far from the actual prescribed volume. Recording of the patient weight or prescribed volume and rate will be needed to estimate the deviations more accurately. Additionally, the MEDRAD injector only recorded peak flows and not median flows which may have contributed to the higher rate of positive deviations. Further evaluation with capturing of the mean flows will be obtained at a later date when available on future software updates.

Conclusion

Differences between the contrast bolus protocol of routine single-phase CT exams of the abdomen-pelvis and the actual amount of contrast delivered to each patient vary with respect to both administered volume and injection rate, with more than 10 % of administrations diverging from assumed values by greater than 10 %. These differences could result in non-diagnostic CT exams when the delivered amount is too low, and can increase the risk of contrast-related complications when too high. Informatics devices that can capture injection profiles such as these are good data sources for quality-assurance projects to identify and correct the causes of this variability.

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