Accuracy of MRI-Compatible Contrast Media Injectors
Genauigkeit von MRT-kompatiblen Kontrastmittelinjektoren

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Abstract
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Purpose: To analyze the exactness of MRI-compatible contrast media (CM) injectors in an experimental setup and clinical use.
Materials and Methods: Ejected fluid volumes and amounts of CM were quantified for single and double piston injections. The focus was on small volumes, as used in pediatric examination and test-bolus measurements. Samples were collected before and after clinical MRI scans and amounts of CM were measured.
Results: For single piston injections the volume differences were minimal (mean difference 0.01 ml). For double piston injections the volume of the first injection was decreased (mean 20.74 ml, target 21.00 ml, p < 0.01). After a position change of the Y-piece of the injection system, the amount of CM differed significantly from the target value (mean 1.23 mmol and 0.83 mmol at 1 ml/s flow rate, target 1.00 mmol, p < 0.01), independently of the wait time. The clinical samples confirmed these findings.
Conclusion: The pistons of modern CM injectors work exactly. However, for small CM volumes the injected amount of CM can differ significantly from the target value in both directions. Influence factors are an incomplete elimination of air and exchange processes between the CM and saline chaser in the injection system.
Key Points:
▶ In MRI examinations of children and test-bolus measurements, small amounts of CM are used.
▶ The accuracy of single piston injections is high.
▶ In double piston injections the injected amount of CM can differ significantly from the target value.

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Zusammenfassung
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Ziel: Ziel dieser Arbeit war die Untersuchung der Genauigkeit von MRT-kompatiblen Kontrastmittel-Injektoren (KM-) im Versuchsaufbau und klinischen Einsatz.
Material und Methoden: Bei zwei KM-Injektoren wurden das abgegebene Flüssigkeitsvolumen und die enthaltene KM-Menge im Einzel- und Doppelkolbenaufbau bestimmt. Der Schwerpunkt lag auf kleinen Flüssigkeitsvolumina, wie sie bei Kindern und Testbolusmessungen verwendet werden. In der klinischen Routine wurden vor und nach MRT-Untersuchungen Proben genommen und die enthaltene KM-Menge bestimmt.
Ergebnisse: Bei Einzelkolbeninjektionen wich die abgegebene Flüssigkeitsmenge nur minimal vom Soll ab (mittlere Abweichung 0,01 ml). Bei Doppelkolbeninjektionen war das Volumen der ersten Injektion erniedrigt (Mittelwert (MW) 20,74 ml, Soll 21,00 ml, p < 0,01). Die tatsächlich abgegebene KM-Menge wich nach einem Lagewechsel des Y-Stücks des Schlauchsystems, unabhängig von einer Wartezeit, signifikant vom Soll ab (MW 1,23 mmol bzw. 0,83 mmol bei 1 ml/s Förderrate, Soll 1,00 mmol, p < 0,01). Die Proben aus der klinischen Routine bestätigten diese Beobachtung.
Schlussfolgerung: Die Kolben moderner KM-Injektoren arbeiten mechanisch sehr genau. Bei kleinen Injektionsvolumina kann die tatsächlich applizierte KM-Menge jedoch signifikant in beide Richtungen vom Sollwert abweichen. Einflussfaktoren sind eine nicht vollständige Entlüftung und Austauschvorgänge im Schlauchsystem zwischen KM und Kochsalzlösung.

Introduction
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An intravenous contrast medium is used during magnetic resonance imaging (MRI) examinations for a number of clinical questions. A gadolinium chelate is typically administered during the examination with the help of an injector. The amount of contrast medium is usually calculated on the basis of body weight with 0.1 mmol contrast medium per kg body weight being the standard dose. Depending on the concentration of the contrast medium, this results in standard volumes for adults of 5 – 20 ml contrast medium followed by a saline bolus of 20 – 30 ml to rinse the injection system and the vein.

In children or in the case of test-bolus measurements for determining circulation time, smaller contrast medium volumes starting at 1 ml are also used. The number of MRI examinations in children has increased in recent years. The most common examination indications are oncological diseases, CNS pathologies, and rare diseases [1 – 3]. In an evaluation of 2335 MRI examinations in children, the median age was 3.5 years corresponding to a body weight of approximately 15 kg and a weight-adapted volume of a 1 molar contrast medium of 1.5 ml [4, 5]. Exact dosing of the amount of contrast medium requires a high degree of precision and accuracy of the injector. Even small absolute volume differences result in high relative deviations in the case of small amounts of contrast medium and could influence the contrast or affect a test-bolus measurement.

The precision of a method describes the agreement between multiple independent individual values under unchanged conditions. Therefore, if the volumes of multiple injections with the same target volume are close together, the injection system has a high degree of precision. The accuracy is a measure of the agreement between the average value of multiple individual values and the reference value. If the average value of the contrast medium volumes is in good agreement with the target value, there is a high degree of accuracy . The exactness indicates the agreement between the individual value and the target value. High exactness requires high precision and accuracy. A contrast medium injector should have a high degree of exactness.

The goal of this study was to examine the exactness of MR-compatible contrast medium injectors in an experimental setup and clinical use.

Materials and Methods
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The two *Medtron Accutron MR* (Medtron AG, Saarbrücken, Germany) double piston injectors used in our department were examined with syringes approved for multiple use, the *Medtron ELS 65 ml* for the contrast medium and the *Medtron ELS 200 ml* for the saline solution, the tube system with Y-piece *Medtron MRS 222 MR* and the *Medtron ES 224/150* patient tube.

Single piston injections

Both injectors were equipped with an *ELS 65* syringe and a patient tube. The system was filled with distilled water at a temperature of 20 °C and vented. Volumes of 1 – 10 ml in increments of 1 ml were dispensed three times with both injectors with flow rates of 1 – 5 ml/s in increments of 1 ml/s.

The fluid was collected each time in a container and the weight was determined via a precision scale. Based on the density of distilled water (0.9982 g·cm⁻³ at 20 °C [6]), the volume and deviation from the target volume were calculated on the basis of the weight.

Double piston injections with distilled water

One injector was equipped with two syringes (*ELS 65* and *ELS 200*), a tube system, and a patient tube. Both syringes were filled with distilled water (20 °C) and the system was vented. Three times in succession (injection series), 1 ml of fluid from the *ELS 65* syringe and 20 ml of fluid from the *ELS 200* syringe were dispensed. The tube system was subsequently changed each time. Each injection series was performed a total of four times with flow rates of 1 – 5 ml/s in increments of 1 ml/s. The dispensed fluid was collected in a container, the weight was determined via precision scale, and the volume was calculated.

CT densitometry

A dilution series of contrast medium with 0.9 % saline solution (Berlin Chemie AG, Berlin, Germany) was pipetted in the dilution increments 1/6 to 1/41. Gadovist (Gadobutrol, Bayer Vital GmbH, Leverkusen, Germany) with a concentration of 1 mmol/ml and a density of 1.3 g/ml (manufacturer specification) was used as the contrast medium. Every test tube was mixed for 30 seconds on a small shaker (IKA MS3 digital, IKA-Werke GmbH & Co. KG, Staufen, Germany) at 3000 rpm. All test tubes were then examined via CT. Spiral CT scans were performed on a 64-row CT unit (Sensation 64, Siemens AG, Forchheim, Germany). An accelerating voltage of 80 kV, a tube current of 1000 mAs, a pitch of 0.45 and a collimation of 64 × 0.6 were selected as the scan parameters. A multiplanar reconstruction (MPR) was created from the dataset through the sample fluid parallel to the air/fluid level (slice thickness 10 mm). A circular ROI was drawn in the MPR in every sample and the CT density of the particular dilution increment in Hounsfield units (HU) was determined. The concentration-density pairs were drawn in a coordinate system and the regression formula (concentration-density formula) and the coefficient of determination of the regression curve were determined.

Double piston injections with contrast medium without a wait time

One injector was equipped with two syringes, a tube system, and a patient tube. The *ELS 65* syringe was filled with Gadovist and the *ELS 200* syringe was filled with a 0.9 % saline solution and the system was vented. Injections of 1 ml of contrast medium and 20 ml of saline solution (test bolus, target contrast medium amount per sample – 1 mmol) were performed twelve times in each case with a flow rate of 1, 2, and 5 ml/s. The position of the Y-piece of the tube system was varied between:

▶ Unchanged upward position of the common tube piece (three times)
▶ Unchanged downward position of the common tube piece (three times)
▶ Varying "upward" (three times) and "downward" (three times) position of the common tube piece

The samples were collected and examined as described above via CT densitometry. The contained amount of con-

trast medium was calculated using the previously determined concentration-density formula.

Double piston injections with contrast medium after a wait time

One injector was equipped with two syringes, a tube system, and a patient tube. The *ELS 65* syringe was filled with Gadovist and the *ELS 200* syringe was filled with a 0.9 % saline solution. The Y-piece was positioned with the common tube piece in an "upward" position and was vented. The position of the Y-piece was switched "from upward to downward" and left in this position three times in each case for 0, 1, 5, 15, 30, and 60 minutes. 1 ml of contrast medium and 20 ml of saline solution were then injected with a flow rate of 1 ml/s. The samples were collected and the contained amount of contrast medium was determined with CT densitometry.

Samples from the clinical routine

To examine the practical relevance of the observations from the experimental setup, samples were acquired in the clinical routine immediately before (N = 33) and after (N = 33) diagnostic MRI examinations. 1 ml of contrast medium and 20 ml of saline solution at a flow rate of 1 ml/s were selected on the injection system. The contained amount of contrast medium was determined via CT densitometry.

Statistical evaluation

The regression analysis was performed with Microsoft Excel 2010 (Microsoft Corporation, Redmond, USA). The remaining data were statistically examined via t-test and variance analysis with Bonferroni correction in SPSS 17 (IBM Deutschland GmbH, Ehningen, Germany).

Results
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Single piston injections of distilled water

In the case of injections of 1 – 10 ml of fluid, the actually dispensed fluid amount deviated only minimally from the target value for all selected volumes regardless of the flow rate and the injector. The measurement results are shown in Table 1.

Double piston injections of 1 + 20 ml of distilled water

During the first injection after replacement of the tube system, the dispensed volume was always lower than in the second and third injections. The univariate variance analysis showed a significant dependence of the dispensed fluid volumes on the number of the injection in the comparison between the first and second and the first and third injection (both $p < 0.01$). The comparison between the second and third injection did not yield a significant difference ($p > 0.05$). Despite careful venting, an air bubble regularly remained in the Y-piece of the tube system and was usually transported with the fluid flow during the first injection, thus reducing the dispensed fluid volume. The dispensed volume was not dependent on the flow rate ($p > 0.05$). The measurement results are shown in Table 1.

CT densitometry

The dilution series evaluation resulted in the following concentration-density formula:
Density (HU) = 6700.7 × concentration (mol/L) + 36.1
Coefficient of determination R^2 was 0.99.

Double piston injections of 1 ml of contrast medium and 20 ml of saline solution without a wait time

Samples taken after a position change of the common tube piece of the Y-piece "from upward to downward" contained a relatively increased amount of contrast medium compared to the target value. Samples taken after a change in position of the common tube piece "from downward to upward" contained a reduced amount of contrast medium. The deviation of the amount of contrast medium behaved inversely to the flow rate. Samples taken with an unchanged "upward" or "downward" position of the Y-piece did not differ significantly with respect to the amount of contrast medium ($p > 0.05$) and only deviated minimally from the target value. In the univariate variance analysis, the dispensed contrast medium volumes depended on the change in position of the Y-piece ($p < 0.01$) and on the flow rate ($p < 0.01$). The measurement results are shown in Table 1.

Double piston injections with contrast medium after a wait time

All samples included an increased amount of contrast medium. The dispensed volume was not dependent on the wait time ($p > 0.05$). The measurement results are shown in Table 1.

Samples from the clinical routine

The average amount of contrast medium in the samples taken before a clinical examination was lower than the target value. The average amount of contrast medium in the samples taken after a clinical examination was higher than the target value. The deviation of the target value was significant in both cases ($p < 0.01$). The measured amounts of contrast medium are shown in Fig. 2.

Discussion
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In our study we were able to show that the volumes dispensed by the pistons of modern contrast medium injectors precisely correspond to the selected volumes. Nevertheless, the actually dispensed contrast medium amount can deviate significantly from the target value, particularly in the case of small contrast medium doses, such as in pediatric examinations or test-bolus measurements.

Single piston injections

When using a single piston, the dispensed volumes only deviated minimally from the target value regardless of the flow rate. The deviations in our measurements were in the range of the measurement accuracy of the precision scale and are not significant for clinical use.

Double piston injections

When using a double piston system, the two tubes coming from the syringes with contrast medium and saline solution are combined via a Y-piece into one common tube that runs

single piston injections of distilled water		
target volume in ml	*average actual volume in ml*	*standard deviation of the actual volume in ml*
1.00	0.99	0.03
2.00	1.99	0.02
3.00	3.01	0.02
4.00	4.00	0.03
5.00	5.01	0.02
6.00	6.02	0.02
7.00	7.03	0.02
8.00	8.02	0.05
9.00	9.04	0.03
10.00	10.03	0.02
double piston injections of 1 + 20 ml distilled water		
	Average actual volume in ml	*Standard deviation of the actual volume in ml*
first injection	20.74	0.07
second injection	21.00	0.03
third injection	20.99	0.03

double piston injections of 1 ml contrast medium and 20 ml saline solution			
position of the Y-piece	*flow rate in ml/s*	*average amount of contrast medium in mmol*	*standard deviation of amount of contrast medium in mmol*
change from upward to downward	1	1.23	0.01
	2	1.13	0.02
	5	1.08	0.01
change from downward to upward	1	0.83	0.02
	2	0.93	0.02
	5	1.01	0.02
always upward	1	1.03	0.01
	2	1.04	0.01
	5	1.02	0.01
always downward	1	1.02	0.02
	2	1.03	0.01
	5	1.03	0.02

double piston injections of 1 ml contrast medium and 20 ml saline solution after a wait time		
wait time in min.	*average amount of contrast medium in mmol*	*standard deviation of amount of contrast medium in mmol*
0	1.20	0.01
1	1.19	0.01
5	1.19	0.01
15	1.20	0.01
30	1.19	0.01
60	1.20	0.01

Table 1 Measured values for single and double piston injections in the experimental setup. For injections of distilled water, the measured values were summed up over all flow rates. The accuracy of single piston injections is very high. In the case of double piston injections, the volume of the first injection after setup and venting of the injection system is regularly reduced. After a position change of the Y-piece of the injection tube, the injected amount of contrast medium differs from the target value, independently of the wait time.

to the patient (○ **Fig. 1**). Our study showed two phenomena at the Y-piece of the tube system that could affect the dispensed amount of contrast medium.

On the one hand, complete venting of the Y-piece required rinsing alternately with contrast medium and saline solution multiple times. Since substantial amounts of contrast medium are wasted in this procedure, rinsing is typically performed only once with contrast medium and then with saline solution in the clinical routine. A small air bubble frequently remains in the Y-piece and is then transported with the fluid flow in the following injection, thus reducing the fluid volume by the air volume.

On the other hand, we observed position-dependent exchange and mixing processes in the contrast medium tube behind the Y-piece that were visible due to schlieren. ○ **Fig. 1** illustrates the processes.

The common tube piece was first directed "upward", the contrast medium tube was filled completely with contrast medium to the Y-piece, and the NaCl tube and the common tube piece were rinsed with saline solution. In an unchanged position, an injection of 1 ml of contrast medium followed by 20 ml of saline solution was performed. There was no exchange between contrast medium and saline solution. The dispensed contrast medium quantity corresponded to the target value.

If the common tube piece was then moved "downward" (corresponding to the "from upward to downward" position change), the contrast medium flowed downward into the
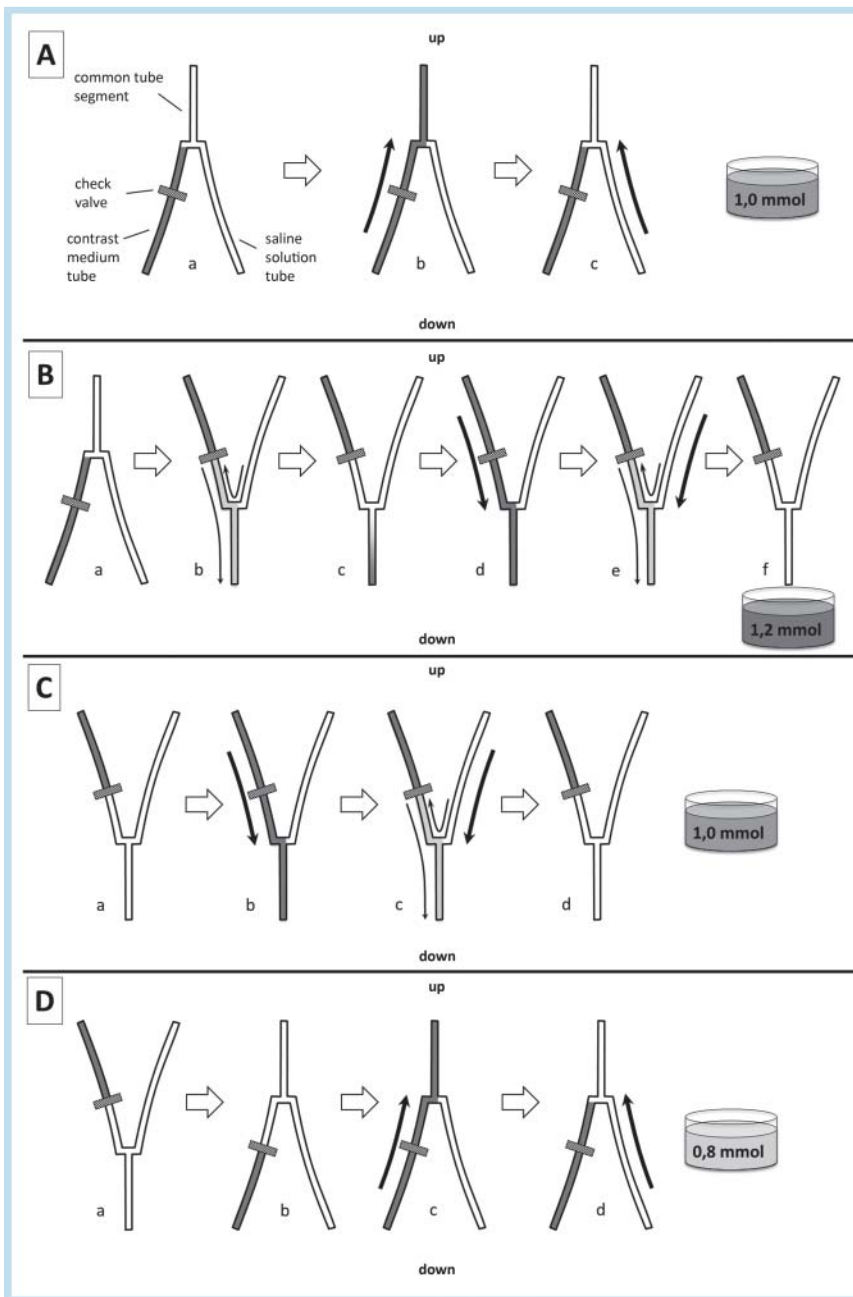
Fig. 1 Position-dependent exchange processes in the contrast medium tube near the Y-piece influence the effectively dispensed amount of CM.
A During the injection of 1 ml CM **b** and 20 ml saline chaser **c** in an unchanged "upward" position of the Y-piece, no exchange between CM and saline takes place. The dispensed amount of CM matches the target value.
B After a position change "from upward to downward", contrast medium flows in the common tube, independently from an injection; saline replaces the contrast medium in the contrast medium tube **b, c**. During a following injection the contrast medium tube is refilled with contrast medium **d** and the process starts again **e**. The dispensed amount of contrast medium in increased.
C In an unchanged "downward" position, the dispensed amount of contrast medium matches the target value. The contrast medium tube is refilled with contrast medium during the contrast medium injection **b**, but the contrast medium is then immediately replaced by saline due to the exchange process **c**. Before and after the injection process, the contrast medium tube is filled with saline **a, d**.
D Following a position change "from downward to upward", the dispensed amount of contrast medium is decreased. Before the injection, the contrast medium tube near the Y-piece is filled with saline **a, b**. During the following injection this saline is transported to the common tube and is replaced by fresh contrast medium, which stays in the injection system **c**.

common tube segment, while the saline solution rose upward and replaced the contrast medium in the contrast medium tube. This procedure began independent of an injection immediately after a change in position and was complete after approximately 20 seconds. An additional wait time of up to 60 minutes, corresponding to the typical wait times of an injector in clinical use, did not affect the dispensed amount of contrast medium. The contrast medium tube was refilled with contrast medium during an injection and the process began again. The amount of contrast medium in samples after a change in position "from upward to downward" was accordingly increased.

In the unchanged "downward" position of the Y-piece, the dispensed amount of contrast medium corresponded to the target value during the next injection. The contrast medium tube was initially refilled with contrast medium as a result of the contrast medium injection but the contrast

medium was again replaced by saline solution due to the immediately following exchange process. Prior to the start and after the end of the injection, saline solution was in the contrast medium tube behind the Y-piece.

In a subsequent change of position of the contrast medium tube "from downward to upward", the dispensed amount of contrast medium was reduced in the next injection since saline solution or diluted contrast medium from the previous injection was still in the contrast medium tube and was then carried into the common tube segment during the subsequent injection and was replaced by the contrast medium from the syringe with a normal concentration.

The lower the flow rate, the greater the average deviation of the amount of contrast medium from the target value during repetitive position changes. This observation may be largely due to the longer injection time at lower flow rates. The exchange process between the contrast medium and
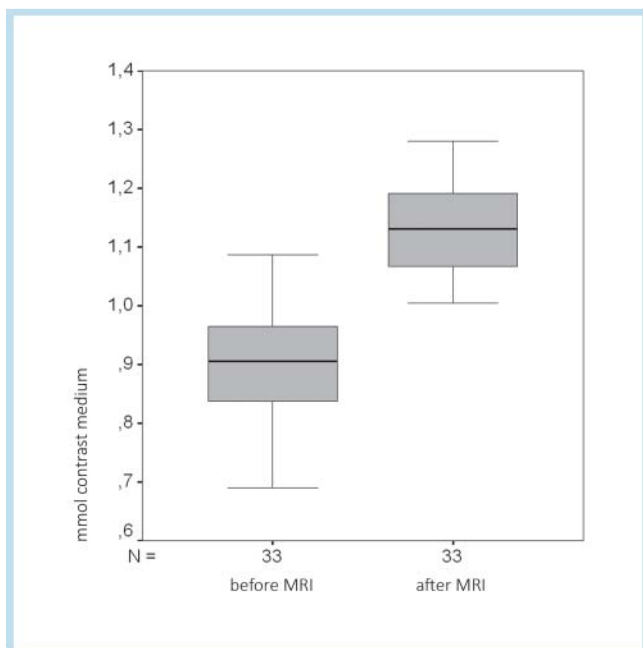
Fig. 2 Amount of contrast agent found in samples before and after clinical MRI examinations. The target quantity is 1 mmol in each case. The mean amount of contrast agent was reduced in samples before MRI (left) and increased in samples after MRI (right). This finding correlates well with the typical changes of position of the injection system before and after MRI examinations.

saline solution in the contrast medium tube took approximately 20 seconds. In the case of a short injection time (approx. 4 seconds at a flow rate of 5 ml/s), this primarily occurred after the conclusion of an injection. The deviation of the amount of contrast medium was correspondingly low. In the case of a long injection time (21 seconds at a flow rate of 1 ml/s), large amounts of the contrast medium in the contrast medium tube were exchanged during saline solution rinsing and were also injected. The deviation of the amount of contrast medium was significantly higher.

The reason for the exchange between the contrast medium and the saline solution is the different densities of the two fluids. The fluid with the greater density always sinks downward. The phenomenon is known from flow mechanics [7, 8]. The density differences between contrast medium and saline solution are also the reason for the observed schlieren.

Rinsing was limited in the examined tube system by a check valve in the contrast medium tube. The tube piece between the check valve and the Y-piece holds a volume of approximately 0.2 ml. This correlates well with the deviations of the amount of contrast medium found in the experimental setup.

Already in 1998, Heverhaben et al. described an unintentional contrast medium injection in connection with the rinsing of an infusion needle from an MRI double-head injector with saline solution. They identified mixing processes between the contrast medium and the saline solution as the cause and recommended the use of check valves and an upward position of the Y-piece [9].

Clinical samples

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Examination of the clinical samples confirmed the occurrence of the above-described effects in the clinical routine. The samples acquired directly before MRI contain the amount of contrast medium received by the patient during the first injection. The tube system is normally left hanging "downward" for venting. (The pistons of the injector point upward. However, their position is not relevant for the described effects.) When the system is connected to the patient, the tube is then tilted upward (position change "from downward to upward") in agreement with the reduced average amount of contrast medium in the samples acquired immediately before MRI. When disconnecting the system after MRI, the tube system is then tilted back down again in agreement with the increased amount of contrast medium in the samples acquired after MRI.

Test bolus

The maximum deviation of the amount of contrast medium from the target value found in the clinical samples was approximately 0.3 mmol. In the case of a 1 molar contrast medium, this corresponds to a volume of 0.3 ml. In relation to the total volume of an injection including a saline bolus (in the case of a test bolus, e. g. 21 ml), this does not result in a relevant deviation of the total injection volume or the injection time. Therefore, an influence on the determination of the circulation time during a test-bolus measurement is not to be expected.

However, the described exchange processes can result in a reduction of the amount of contrast medium and possibly in a changed bolus geometry. This could cause a reduced signal-to-noise ratio of the test-bolus measurement so that the measurement can no longer be evaluated. In agreement with this, Janka et al. reported that the signal-time curve is not usable significantly more frequently in the first of two consecutive test bolus injections [10]. A non-evaluable test bolus measurement results in a loss of time due to a repetition of measurements and increased consumption of contrast medium. An improvement of the exactness of the injection system could therefore result in an increase in efficiency and reduced contrast medium consumption (costs, nephrogenic systemic fibrosis).

Practical consequences

According to our knowledge, all currently available tube systems are equipped with permanently installed check valves. According to our results, these limit the possible deviation of the amount of contrast medium to the volume of the tube between the check valve and Y-piece. Therefore, the tube piece between the check valve and the Y-piece should be as short as possible or the check valve should be integrated in the Y-piece. However, this design change can only be made by the manufacturer of the injection tube. Until optimized tube systems are available, the user should therefore secure the Y-piece with the common tube piece in an upward position (e. g. by securing it to the injector with tape). In our experience, air bubbles occur less frequently in the Y-piece when venting is performed with a very slow flow rate. The amount of contrast medium possibly deviating from the target value and a consequently

changed image contrast should then be taken into consideration when interpreting MRI examinations.

Limitations

Limitations of our study are the use of an injection system of only one manufacturer and one contrast medium. However, since a basic physical principle (density difference) is responsible for the described phenomena, these should be similar in all injection systems. In the case of low-concentration contrast media, the deviation of the amount of contrast medium is presumably lower. Moreover, we did not examine any CT or DSA injectors. Due to the design of these injectors that is comparable with the examined MRI injector and the also present density differences between iodine-containing contrast medium and saline solution, we expect the occurrence of exchange processes for these injectors as well. However, since the injected contrast medium volumes are typically significantly greater in the case of iodine-containing contrast media, the relative error should be lower and fade to the background.

Summary

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The pistons of modern MRI-compatible contrast medium injectors are mechanically very exact. In the case of small injection volumes as used in children and test-bolus measurements, the actually applied amount of contrast medium can deviate from the target value significantly in both directions in exact of double piston injections. Influence factors are incomplete venting of the tube system and exchange processes between the contrast medium and the saline solution in the tube system.

Clinical relevance of the study

▶ In MRI examinations of children and test-bolus measurements, small contrast medium volumes are injected with injection systems.

▶ The amount of contrast medium dispensed by double-piston injectors can deviate from the target value significantly in both directions.

▶ Influence factors are incomplete venting of the tube system and exchange processes between the contrast medium and the saline solution in the tube system.

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