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Quantifying the financial savings of motion correction in brain MRI

A model-based estimate of the costs arising from patient head motion and potential savings from implementation of motion correction

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Abstract

Background: Patient head motion is a major concern in clinical brain magnetic resonance imaging (MRI), as it reduces the diagnostic image quality and may increase examination time and cost.

Purpose: To investigate the prevalence of MRI images with significant motion artifacts on a given clinical scanner and to estimate the potential financial cost-savings of applying motion correction to clinical brain MRI examinations.

Study Type: Retrospective

Subjects: 173 patients undergoing a PET/MRI dementia protocol and 55 pediatric patients undergoing a PET/MRI brain tumor protocol. The total scan time of the two protocols are 17 and 40 minutes, respectively.

Field Strength/Sequences: 3T, Siemens mMR Biograph, MPRAGE, DWI, T₁ and T₂-weighted FLAIR, T₂-weighted 2D-FLASH, T₂-weighted TSE.

Assessment: A retrospective review of image sequences from a given clinical MRI scanner was conducted to investigate the prevalence of motion corrupted images. The review was performed by three radiologists with different levels of experience using a three step semiquantitative scale to classify the quality of the images. 1013 sequences distributed on 228 MRI examinations were reviewed. The potential cost-savings of motion correction were estimated by a cost-estimation for our country with assumptions.

Statistical Test: The cost-estimation was conducted with a 20 % lower and upper bound on the model assumptions to include the uncertainty of the assumptions.

Results: 7.9 % of the sequences had motion artifacts that decreased the interpretability, while 2.0 % of the sequences had motion artifacts causing the images to be nondiagnostic. The estimated annual cost to the clinic/hospital due to patient head motion per scanner were \$45,066 without pediatric examinations and \$364,242 with pediatric examinations.

Data Conclusion: The prevalence of motion corrupted image was found in 2.0 % of the reviewed sequences. Based on the model, repayment periods are presented as a function of the price for applying motion correction and its performance.

Keywords

Neuroimaging

Motion Correction

Motion Artifacts

MRI

Cost Saving

INTRODUCTION

Magnetic resonance imaging (MRI) is an important imaging modality for patient diagnosis and research, and brain MRI is performed worldwide. However, MRI requires longer acquisition times when compared to computed tomography (CT), and patients need to lie still in a narrow and often loud scanner bore. A typical brain examination includes 4 to 6 sequences, each taking 2 to 6 minutes, requiring the patient to lie in the scanner for more than 20 minutes. Such long examinations can make MRI an uncomfortable and stressful experience for the patients. Due to the long acquisition times and uncomfortable environment, patient head motion is a major concern in brain MRI, as motion impairs the diagnostic quality of the images. Recent advancements of high field MR scanners allowing improved spatial resolution (1), are even more sensitive to small motions since the threshold for destructible subject motion decreases with the spatial resolution (2, 3). Gretsche et al reported in (4) that 33 out of 36 MP2RAGE scans with a 0.5mm isotropic resolution of healthy volunteers have visual artifacts related to motion. The volunteers were instructed to remain motionless during the scans and only small motion due to e.g. breathing or swallowing were observed.

The consequences of head motion during image acquisition are low-quality images corrupted by artifacts, known as ghosting, ringing, and blurring (5). This degradation in image quality makes the interpretation more difficult and increases the risk that the radiologist may overlook key diagnostic features. Repeating one or more of the MRI sequences is often necessary to obtain images of sufficient diagnostic quality, but at the expense of prolonged examination time causing increased patient stress and discomfort, and a lower patient throughput. According to a recent study, repeated sequences were necessary in 19.8 % of the MRI examinations,

adding an extra cost of approximately \$115,000 per scanner per year (6). Thus, motion not only increases patient discomfort by prolonging the examination, but also adds additional costs for the hospital. Sedation or anesthesia are commonly used in pediatric examinations to avoid motion, but these methods come with risks (7, 8) and costs. Vanderby et al (9) reported that an MRI examination using sedation or anesthesia increased the total examination-costs by a factor of 3 and 10, respectively.

To reduce the negative impact of head motion, numerous motion mitigation techniques have been proposed (10, 11).

While there is much work devoted to developing new and better solutions for motion correction, the potential financial benefits of motion correction have not been thoroughly investigated. Hence, the focus of this work was on qualifying, in an extreme model, the costs of motion degradation.

MATERIALS AND METHODS

Data

Two examination protocols with 228 patients in total were selected for this study: one investigating dementia patients (N=173), and one investigating pediatric patients (N=55) with brain tumors including both pre- and post-operative examinations. The median ages were 73 years (range 17 - 94 years) and 11 years (range 1 month - 19 years), respectively. Both hybrid Positron Emission Tomography (PET)/MRI protocols were performed on an mMR Biograph hybrid 3T PET/MRI scanner (Siemens Healthcare, Erlangen, Germany). The pediatric study was approved by The Danish National Committee on Health Research Ethics (ID: H-6-2014-095)

and registered at clinicaltrials.gov (NCT03402425), and all patients/parents gave written informed consent for participation in the study. For the dementia protocol the retrospective use of patient data was approved by the Danish Patient Safety Authority (ref. 3-3013-1513/1).

Only diagnostically used MRI sequences were evaluated, whereas all PET and PET related MRI sequences, e.g. for planning and attenuation correction, from both protocols were excluded, in order to be able to generalize to non-hybrid MRI scanners. Examinations, using sedation or anesthesia were excluded since these patients were assumed to remain motionless during the examination.

Review of MRI Images

Three MRI radiologists (years of experience. HJ; 19 years, PM; 4 years AS; 5 years) visually reviewed all sequences uploaded to PACS (General Electric, Milwaukee, Wisconsin) from the two selected protocols and assigned a quality score to each image volume. The quality score is divided into three groups: score 1 = Images optimal for clinical use, score 2 = images useful for diagnosis, but not optimal, and score 3= non-diagnostic images, i.e. requiring a repeated scan. The radiologists were instructed to assign the quality score based only on the severity of motion artifacts. Images with minor motion artifacts appearing on a single slice or with artifacts other than motion were classified as optimal for clinical use (score 1). Images were scored individually by the three radiologists and the median score was used as the final image score. The inter observer variability is given by the number of sequences with; all equal scores, two equal scores, and all different scores as the fraction of the total number of evaluated sequences.

Estimation of Motion Induced Costs

The financial costs of head motion were estimated in four different cost categories described below. Cost category 1), 2), and 4) estimated the motion related costs to the clinic or hospital while 3) estimated the additional costs to society other than to the clinic and hospital, as described below. The four cost categories were based on an MRI scanner performing 2,000 brain examinations per year, corresponding to eight examinations per day with the scanner operating only on weekdays. The average examination contained five sequences, based on the number of non-PET related sequences in the two selected protocols. All assumptions used to estimate 1) – 4) are summarized in Table 1. Values for lower and upper ranges are also shown, to specify the uncertainty for each assumption.

Cost categories 1) to 4) estimates the following:

- 1) The added extra costs to the clinic when motion corrupted images are detected and repeated during the examination. The added costs are estimated from the perspective of the Department of -----, Denmark. Here, the cost of a standard head MRI examination is \$555 per hour inclusive of costs for the radiologist, radiographers, and other staff. Extra examination costs related to gadolinium administration, sedation, or anesthesia were not considered here in order to simplify the assumptions. Based on our image quality review outlined in the next section, it is assumed that the probability that a given sequence must be repeated is 2.0 %. In a previous study this was 5.5 %, and this is used as an upper bound (6).

- 2) The additional costs to the clinic when motion corrupted images are not detected or repeated during the examination. Examinations with motion corrupted image volumes add additional inspection time to the radiologist and if essential images are non-diagnostic, a reexamination must be conducted. The additional time to review and to refer the patient to a new MRI examination by a radiologist is assumed to be 20 minutes per examination and it is assumed that the hourly rate of the radiologist is \$111. Our review of 1013 sequences uploaded to PACS showed that 4.4 % of the examinations contained at least one non-diagnostic sequence.
- 3) The additional costs to the society, as lost working earnings from the scanned patients, due to prolonged examination time. Due to the problem of head motion, it is a common practice in the department to add a 30 minutes time buffer in our patient information, so that patients are prepared if motion corrupted sequences need to be repeated. Due to this precaution every patient loses 30 minutes. Our cost categories are estimated from the perspective of the Danish society, where the average working earning rate for Danish citizens is approximately \$33 per hour (12). Not all scanned patients have jobs and for them the time buffer will not result in lost working earnings. It is assumed that 50% of the examined patients are within the working age (18-70 years) and that 50% of these patients are not able to maintain a job, due to their physical condition. Hence 25% of the scanned patients are assumed to be working on the day of the MRI examination. For simplicity, patients accompanied by a relative is also represented in the 25%.
- 4) The additional costs to the hospital or clinic when anesthesia is necessary to avoid motion in pediatric examinations. Anesthesia is a common tool to minimize motion in pediatric

patients and remove the risk of motion corrupted images. At our target department, a pediatric MRI examination with anesthesia increases the cost by \$4433. The number of pediatric examinations and the use of anesthesia varies between scanner sites. In our model, it is assumed that 10% of the examinations are pediatric, and that 36% of the pediatric patients are anesthetized during the examination. These expenditures can either be on the budget of the imaging department or the hospital depending on the hospital administration.

On top of the costs listed above, there are costs to informal care-givers and family, which might be reduced by reducing motion artifacts, as their time spent at the hospital may be shorter and their anxiety may be reduced. Patients may also be anxious and worry if their movements might impair the quality of their scan. These costs are not well documented and difficult to estimate and have not been included in the model.

Savings When Implementing Motion Correction

The potential repayment period when implementing motion correction in a clinical workflow depends on the cost of subject motion, the motion correction implementation cost, and the performance of the implemented solution. Due to differences in correction strategies, the performance or the fraction of motion corrupted sequences that can be corrected depends on the correction method itself. Performance and implantation cost comparison of various motion correction methods are not the purpose of this article. The correction performance and implementation cost are therefore leaved as function variables in the cost saving model. The potential repayment period of a motion correction solution is estimated as a function of the total cost and the performance of the implemented motion correction solution, given

as

$$f(c, s) = \frac{c}{\sum_i [\text{Cost category } i] p} , \quad (1)$$

where f is the repayment period, c is the implementation cost, and p is the motion correction performance rate. *Cost category i*) corresponds to the additional cost due to subject motion as previously described in cost categories 1) to 4). It is assumed that all adult patients complete their scans. This is not the case for pediatric patients, where anesthesia is necessary to avoid motion and even to keep the child in the scanner. Even with perfect motion correction some pediatric patients still need anesthesia, for whom motion correction will not have cost saving effects. Runge et al. (13) suggested a children centered care solution to reduce the number of examination with anesthesia of 4 to 10 years old children. The concept was tested on 41 children 4 to 6 years old and 95 % of the examinations were successfully completed without anesthesia. Anesthesia rates are in the literature reported to 47% to 75% (13) for children in the age 4 to 10 years. It is assumed that the age of the scanned children is uniformly distributed and children older than 11 years are scanned without anesthesia. Thus, the group of 4 to 10 years old children corresponds to 64% of all scanned children < 11 years old. This results in 30% to 48% of the pediatric patients scanned with anesthesia are 4 to 10 years old. Using a similar solution as in (13) together with motion correction with a combined success rate on 95% (76% lower bound and 95% upper bound), is it assumed that 37% (46% upper bound, 23% lower bound) would be able to complete a standard examination. Hence, prior to estimating the repayment period in Eq. (1) 37% (46% upper bound and 23% lower bound) of cost category 4) is used. The total implementation cost of motion correction would also include the cost of a solution similar to children centered care.

RESULTS

Prevalence of Motion Corrupted Images

For the review, 228 MRI examinations from a period between March 2015 and December 2017 were included with a total of 1013 sequences. One hundred and seventy-three (76 %) of the examinations were from the dementia protocol and 55 (24 %) from the pediatric protocol. The radiologists reviewed all 1013 sequences and assigned a quality score according to the severity of motion artifacts to each sequence. In 85.7 % of the reviewed sequences the same score were assigned by all three radiologists. In 14.0 % one score were assigned differently and in 0.3% all scores were different. Fig 1 shows example MPRAGE sequences assigned with a score from 1 to 3, respectively. The left chart in Fig 2 summarizes the results of the review. It shows that 913 (89.8 %) of the acquired sequences contain no or minimal motion artifacts and the image quality was optimal for clinical use. It also shows that 80 (7.9 %) of sequences were corrupted by motion to a degree that it decreased the diagnostic utility and 20 (2.0 %) of these sequences could not be used for diagnostics purposes and should be repeated. Out of the 100 motion corrupted sequences 23, 20, and 57 were acquired in the first, second, and third part of the examination, respectively. The total raw image acquisition-time for those 100 sequences is approximately four and a half hours, which is equal to 3 minutes per sequence.

The chart to the right shows the distribution of the 228 MRI examinations with 10 (4.4 %) of the examinations containing one or more sequences that needed to be repeated.

Estimation of Motion Induced Cost

Results of the four estimated cost categories are presented in Table 2 together with the assumptions used for each. The sum of the costs in category 1), 2), and 4) are the annual costs to the department or hospital: \$364,242 per scanner. Results using the lower and upper bounds are \$150,101 and \$785,795 per scanner per year, respectively. The total cost to society is \$372,492 per scanner per year as the sum of the costs estimated in cost category 1), 2), 3), and 4), and the results using the lower bound values: \$154,325 and upper bound values: \$800,051 (Table 2).

Savings When Implementing Motion Correction

Using the above estimated costs, the potential repayment period when implementing motion correction in a clinical workflow is shown as a function of cost and performance in Fig 3.

From the figure it is seen that a motion correction solution for adult scans only (top row) with a total cost of \$100,000 would be financially viable for the hospital after 5 years if it achieves correction performance of at least 45% (16% for upper bound). The same solution would be viable after 3 years if 75 % performance is achieved. Based on the conservative lower bound estimates, such a solution with 45 % performance would be financially viable after 12 years.

DISCUSSION

MRI is the method of choice for diagnosis of patients with brain diseases and for research in neurobiology. However, the acquisition time is often long and during the scan, patients must lie still in a narrow and noisy scanner bore, making MRI examinations uncomfortable. This increases the risk of patient motion impairing image quality.

In this work, the prevalence of motion corrupted images was studied by reviewing 1013 sequences from 228 MRI examinations. Further, a model-based estimate was used to estimate the financial costs of head motion and to determine if implementation of motion correction is cost-saving.

We found that 4.4% of the MRI brain examinations had sequences that were corrupted by motion artifacts to such an extent that they had to be repeated.

It is important to note, that the two patient populations are considered particularly prone to motion and the cost-saving estimates are likely exaggerated. However, another study that was performed across a broader patient population and a wider range of illnesses, reported that 19.8% of the exams contained repeated sequences (6).

The suggested cost analysis indicates that the implementation cost of a perfect (100% performance) motion correction solution on an adult population, must not be more than \$225,300 (\$91,990 lower bound and \$634,500 upper bound), if the solution should be financially viable after five years. However, it is unlikely that a motion correction solution would have 100 % performance on any sequence under any motion condition. A more reasonable motion correction solution with a performance on 50% would result in a maximal implementation cost of \$47,000, using the most conservative model assumptions for the adult population. Applying the same solution and conservative assumptions to a mixed population with 10% pediatric, the highest implementation cost is \$132,500. However, this implementation cost is also including the cost of extra preparation of the pediatric patients to make them complete their examination.

Kecskemeti et al. (14) reported that retrospective motion correction of MRRAGE sequences

was able to increase image quality from *unusable* to *good for clinical use* in all of the 7 sequences. Applying such a solution in our setting with 5 sequences per examination results in a performance of 20% since this solution is only available for MPRAGE sequences. Based on our suggested cost analysis, such a motion correction solution would be cost saving after five years if the implementation cost is below \$45,000 (\$18,400 lower bound \$127,000 upper bound) for the adult population.

Besides the financial benefits to the clinic, hospital and society, motion correction decreases the need for rescans, results in shorter examination times leading to increased comfort of the patients. Other non-financial benefits to the patients include reduced patient anxiety for causing motion problems. For relatives and informal care-givers, reduced anxiety and reduced waste of time are important. These costs have not been included in our model. Also, patient time costs include only lost work hours and not shadow prices or lost leisure time.

In pediatric examinations, anesthesia is often necessary to avoid patient motion in order to obtain images of sufficient quality, or just to keep the patient in the scanner. It is expected that motion correction reduces the use of anesthesia especially for the group of older children. It is of great importance to minimize the use of anesthesia due to the associated health risks and the discomfort to patient and relatives. Further, there would be substantial financial benefits to the clinic if anesthesia rates could be reduced using motion correction as seen from cost category 4).

A recent study (15) concluded that it is essential to reduce motion artifacts to increase reproducibility and credibility of neuroreceptor studies in research protocols. The costs related to a

reduction of such methodologically flawed studies are difficult to estimate, but likely substantial.

The additional cost due to repeated sequences in an MRI examination, estimated in cost category 1) is comparable to the cost estimated by Andre et al. (6). However, our estimated costs are generally lower, as the number of MRI examinations per scanner per year was assumed to be 2000 compared to 3588 in Ref. (6).

In the estimated cost of subject motion, it was assumed in cost category 2) that patients would get a standard reexamination if the previous examination could not be used for diagnostics.

This may not be the case for patients where all means were tried to obtain images with sufficient quality in the ordinary examination and these patients would not get a standard reexamination. No additional cost is therefore added in these cases where reexaminations is not performed, which results in overestimated cost.

The cost analysis was conducted as a model-based estimate with assumptions, thus no prospective studies were made in order to estimate the net cost of motion correction. This implies uncertainty in the estimated costs and repayment period. Therefore, the analysis was conducted including 20% lower and upper bounds. However, no investment recommendation can be given before pilot motion correction installations have shown a proven cost advantage.

The estimated costs and savings are a result of the value assumptions based on our clinic in Denmark. The assumed values are specific to Denmark and values for usage of scanners, payment to radiologist, working value in the society at large etc. will differ in other countries (16). In particular, the values for <MRI examination cost per hour>, <MRI examination cost

with anesthesia>, <Hourly rate of a radiologist>, and <Lost earnings to the society per hour> must be changed to represent other specific countries.

In Conclusion, it was found that 2.0 % of the reviewed MRI brain sequences were corrupted by motion artifacts to a degree that they could not be used for diagnostics. Model calculations with assumptions were used to estimate the financial costs of head motion to the Danish society. These costs were used to estimate repayment periods of motion correction as functions of correction performance and implementation cost.

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Table 1 List of assumption used in the four model calculations.

Assumption	Model	Range *)	Explanation
	Value		
Number of MRI neuro examinations per scanner per year	2000	1600 - 2400	Correspond to 8 examinations per day if the scanner is operating only at weekdays
The fraction of re-	2.0 %	2.0 % - 5.5 %	Prevalence of Motion Corrupted Imag-

peated MRI sequences			es. The upper bound is equal to the findings in (6).
Number of MRI sequences per examination	5	4 - 6	Average number of sequences per examination
Added time per repeated sequence	5 min	4min - 6 min	The added time is equal to the sum of the time needed by the scanner operators to prepare a new sequence and the actual duration of the new sequence.
MRI examination cost per hour	\$555	\$444 - \$666	The cost of an MRI examination at Department of -----.
MRI examination cost with anesthesia	\$4,433	\$3,546 - \$5,320	Additional cost of a brain MRI examination, where the pediatric patient is anesthetized during the examination.
The fraction of MRI examinations that needs to be repeated	4.4 %	3.5% - 5.3%	See section (Prevalence of Motion Corrupted Images).
Added work time to radiologists	20 min	16 min - 24 min	When an uploaded examination contains one or more non-diagnostic sequences, a radiologist uses additional time to conclude that the images are not

			suited for diagnostic and order a new examination.
Duration of new MRI examination	40 min	32min - 48min	Scan time plus patient preparation.
Hourly rate of a radiologist	\$111	\$89 - \$133	Hourly rate of a radiologist at Department of -----.
The fraction of patients working	25%	20% - 30%	We assume that 50 % of the examined patients are within the working age (18-70 years) and 50 % of this group are not able to maintain a job, due to their illness.
Lost working time per examination	30min		A 30 minutes time buffer is added to every examination in case that motion corrupted sequences need to be repeated.
The fraction of pediatric examinations	10 %	8%, 12%	Assumption will depend on case mix
The fraction of pediatric examinations using sedation or anesthesia	36 %	29% - 43%	36 % of the reviewed examinations in the pediatric protocol were performed with sedation or anesthesia.
Lost earnings to the society per hour	\$33	\$26 - \$40	

MRI = Magnetic Resonance Imaging

**) Values used for our model are average value or lower bound, which ever seems most correct. This choice was made to avoid overestimating the cost savings of implementing motion correction. Assumptions are dependent on local health care costs; please see discussion for further considerations.*

Table 2 Results of the costs in category 1)-4).

Model	Lower	Upper
result	bound	bound

Cost category 1) Costs due to repeated sequences

Number of examinations per year	2000	1600	2400
Number of sequences per examination	5	4	6
The fraction of repeated sequences	2.0 %	2.0 %	5.5 %
Added time per rescan	5 min	4 min	6 min
Examination cost per hour	\$555	\$444	\$666
The extra costs to the clinic per scanner per year	\$9,250	\$3,789	\$52,747

Cost category 2) Costs due to repeated examinations

Number of examinations per year	2,000	1,600	2,400
The fraction of repeated examinations	4.4 %	3.5 %	5.3 %
Added work time to a radiologist	20 min	16 min	24 min
The hourly fee to a radiologist	\$111	\$89	\$133
Examination cost per hour	\$555	\$444	\$666
Duration of new examination	40 min	32 min	48 min
Additional cost to the clinic per scanner per year	\$35,816	\$14,670	\$74,268

Cost category 3) Costs due to lost work from the patients

Number of examinations per year	2,000	1,600	2,400
The fraction of patients in work	25 %	20 %	30 %
Lost working time per examination	30 min	30 min	30 min
Hourly working value	\$33	\$26	\$40
Additional cost to the society per scanner per year	\$8,250	\$4,224	\$14,256

Cost category 4) Cost due to anesthesia

Number of examinations per year	2,000	1,600	2,400
Fraction of pediatric examination	10 %	8 %	12 %
Fraction of examinations using anesthesia	36 %	29 %	43 %
Cost of MRI examination with anesthesia	\$4,433	\$3,546	\$5,320
Additional cost to the clinic per scanner per year	\$319,176	\$131,642	\$658,779
Cost categories combined			
Cost category 1) + 2)	\$45,066	\$18,459	\$127,015
Cost category 1) + 2) + 3)	\$53,316	\$22,683	\$141,271
Cost category 1) + 2) + 4)	\$364,242	\$150,101	\$785,795
Cost category 1) + 2) + 3) + 4)	\$372,492	\$154,325	\$800,051

Figure Legends

Figure 1. Sagittal slices from MPRAGE sequences assigned with a score from 1 to 3.

Figure 2 Left; summarizes the review of 1013 sequences, where each sequence is classified into one of three classes. Right; shows the distribution of 228 magnetic resonance imaging (MRI) examinations classified into the same three classes based on the sequence with the lowest quality.

Figure 3. Repayment period as a function of the price for implementing motion correction and the performance of the implemented motion correction solution. Each line indicates an iso repayment level in years. Top row; Repayment periods based on costs from an adult population only (the sum of cost category 1) and 2)). Middle row; Repayment periods based on costs from a mixed population with 10% pediatric patients (the sum of cost category 1), 2), and 4)). Bottom row; Repayment periods based on costs from a mixed population with 10% pediatric patients and the cost of lost earnings to the society (the sum of cost category 1), 2), 3), and 4)).

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JMRI_27112_Fig2.tif

JMRI_27112_Fig3.tif

Quantifying the financial savings of motion correction in brain MRI

A model-based estimate of the costs arising from patient head motion and potential savings from implementation of motion correction

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