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Towards Quantifying the Prevalence, Severity, and Cost Associated With Patient Motion During Clinical MR Examinations

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Abstract

Purpose: To assess the prevalence, severity, and cost estimates associated with motion artifacts identified on clinical MR examinations, with a focus on the neuroaxis.

Methods: A retrospective review of 1 randomly selected full calendar week of MR examinations (April 2014) was conducted for the detection of significant motion artifacts in examinations performed at a single institution on 3 different MR scanners. A base-case cost estimate was computed from recently available institutional data, and correlated with sequence time and severity of motion artifacts.

Results: A total of 192 completed clinical examinations were reviewed. Significant motion artifacts were identified on sequences in 7.5% of outpatient and 29.4% of inpatient and/or emergency department MR examinations. The prevalence of repeat sequences was 19.8% of total MRI examinations. The base-case cost estimate yielded a potential cost to the hospital of \$592 per hour in lost revenue due to motion artifacts. Potential institutional average costs borne (revenue forgone) of approximately \$115,000 per scanner per year may affect hospitals, owing to motion artifacts (univariate sensitivity analysis suggested a lower bound of \$92,600, and an upper bound of \$139,000).

Conclusions: Motion artifacts represent a frequent cause of MR image degradation, particularly for inpatient and emergency department patients, resulting in substantial costs to the radiology department. Greater attention and resources should be directed toward providing practical solutions to this dilemma.

Key Words: MRI, motion, cost estimate, economics, motion correction

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INTRODUCTION

Patient motion can be a frequent cause of image degradation in MR examinations (estimated to occur in 10% to 42% of sequences in a select adult population) [1]. Associated motion artifacts (such as ring artifacts and image blurring) may result in suboptimal image quality that negatively affects radiologic interpretation [2-5], potentially impacts patient safety, and increases the

medicolegal risks associated with interpreting motion-degraded images. Motion artifacts can worsen when advanced MR techniques that rely on higher spatial resolution and involve greater sequence complexity are used [3,5-7]. Surprisingly, the prevalence and severity of motion artifacts that result in significantly degraded clinical MR examinations is poorly documented in the literature, as is their impact on throughput and organizational finances. Although several motion-correction techniques have been proposed [8-16], the newest and most promising methods are available primarily in the research domain, outside the realm of routine clinical use where they might be of substantial benefit.

Motion artifacts may be recognized at the time of image acquisition. At our institution, MR technologists are instructed to repeat sequences that depict significant motion artifacts (with input from the radiologists, when

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possible). Nonetheless, correcting for motion artifacts can extend the time (and possibly increase patient discomfort) associated with an MR examination, which affects patient and provider time, hospital cost, and other resources associated with imaging.

Furthermore, nothing guarantees that patients will be better able to lie motionless during the repeated sequence, and the additional time requirements to have them try to do so have not been previously evaluated. We sought to assess the prevalence of significant motion artifacts and repeat sequences identified on MR examinations obtained in a clinical population at an academic, level I trauma center, with a focus on examinations of the neuroaxis. In addition, we sought to estimate the potential financial loss associated with motion artifacts during MR examinations.

METHODS

A retrospective, HIPAA-compliant study, approved by an institutional review board, was undertaken; patient consent was waived. This study included radiologic review of 1 full, randomly selected calendar week (April 2014) of clinical MR examinations sent to a Centricity PACS (General Electric, Milwaukee, Wisconsin), by neuroradiologists who were blinded to all medical history, clinical presentation, and patient disposition (ie, whether imaging occurred for an outpatient [OP], inpatient [IP], or emergency department [ED] patient). Cases were identified on the scanner console and subsequently sent for image evaluation on PACS.

All examinations were performed at a single hospital, on 3 different MR scanners: a 1.5-T OP-only scanner (Avanto; Siemens Healthcare, Erlangen, Germany) operating on weekdays only, and 2 in-hospital scanners: a 1.5-T SignaHD (GE Healthcare, Milwaukee, Wisconsin) and a 3-T Tim Trio (Siemens Healthcare, Erlangen, Germany). The in-hospital scanners operate 24 hours per day, 7 days per week, and can accommodate IP, ED, and OP examinations.

A preliminary evaluation identified that not all attempted sequences and/or failed examinations are consistently sent to PACS [17]. That is, MR technologists may refrain from sending some failed or interrupted sequences to PACS. However, all these unsuccessfully attempted sequences and/or examinations remain available for review directly on the MR console.

Data Acquisition and Analysis

In recognition of the preceding observation, a radiologic review of all attempted sequences and examinations was

first performed directly at each independent MR scanner console (each attempted examination was reviewed daily at the scanner console, and cross-referenced with the MR schedule for that day, to ensure that no examinations were bypassed). The data obtained directly from the scanner consoles included recordings of all individual sequence acquisition times (beginning to end), scan times for original and repeat sequences, and recordings of the total number of sequences attempted per examination. The preparation (lag) time between acquired sequences was not recorded. This documentation was performed independently, in blinded fashion, by 3 neuroradiologists (who had 6, 36, and 5 years of experience, respectively). They recorded the temporal duration of each MR examination, the number of repeat sequences, the fact that the sequence repeat was due to patient-related motion artifacts (rather than technical or other sources), the time lost per sequence (when repeated), and the number of sequences and examinations that were prematurely terminated.

PACS Review

All acquired images that were part of the final clinical examination were visually reviewed by 2 blinded neuroradiologists at a PACS station to achieve consensus, for detectable motion artifacts. A graded 5-tier scale was devised to incorporate the impact of motion artifacts on diagnostic image quality (Table 1). Using this scale, moderate and severe motion artifacts were judged to negatively affect clinical interpretation of the images. Subtle movements of the globes, pulsation artifacts, breathing and cardiac-related motion, and minimal motion artifacts appearing on a single imaging slice were disregarded in all examinations.

Typical Patient Population

This study was performed across a broad patient population with a wide range of illnesses. Our institution has a focus on neurologic diseases (especially vascular, traumatic, and infectious), spinal axis abnormalities (both traumatic and degenerative), and musculoskeletal diseases. Most ED patients for whom an MR examination is requested are admitted. Their MR examinations are subsequently performed when they are IPs, to facilitate nursing support during the scanning process.

Time and Cost Estimation

The cost estimation was done from an institutional perspective, using a simplified average of recently available

Table 1. Scale used for the clinical quantification of motion artifacts

Artifact Quantification	Definition	Requisite Action
None	Motion artifacts are not detectable.	None
Minimal	Motion artifacts are barely detectable, present on >1 imaging slice, and with <i>negligible effect on image quality and interpretation</i> .	None
Mild	Motion artifacts are noticeable but examination remains diagnostic in quality (ie, identifiably imperfect examination and potentially annoying artifacts, but <i>likely of no diagnostic consequence</i>).	None
Moderate	Motion artifacts degrade and possibly obscure detection of underlying anatomy and pathology, with uncertain, <i>potentially significant diagnostic consequences</i> (ie, rendering a final diagnosis uncertain).	Sequence or examination is (at best) marginal in diagnostic quality and <i>should be repeated</i> .
Severe	Motion artifacts result in markedly distorted underlying anatomy and possible obscured pathology.	Sequence or examination is nondiagnostic in quality and <i>must be repeated</i> .

OP Medicare reimbursement rates (fiscal year 2012) and institutional cost estimates. Differences in US reimbursement systems for IP, OP, and ED patients, including geographic variation and technical and/or professional fee complexity, were not accounted for, owing to the lack of a single, national standard. We used a routine noncontrast MR examination of the brain (Current Procedural Terminology [CPT] code 70551) to estimate OP MR financial implications. For IP financial implications, institutional operational cost estimates were used of modality-specific budget calculations and CMS-mandated relative value units (RVUs) per CPT codes, and patient volumes.

For institutional costs, unit RVUs (for each modality-specific CPT code) were multiplied by examination-specific patient volumes to obtain comprehensive modality expenses and average costs per RVU. The average cost per RVU was used to estimate a procedure-level cost for a specific CPT. CMS reimbursement amounts were used to approximate OP-based costs resulting from repeat imaging. For simplicity, and consistent with our general distribution of patients, we assumed that 50% of scan time lost as a result of motion was for imaging of IPs, and 50% was for imaging of OPs. Thus, the costs of repeat imaging were estimated to be an average of additional IP cost incurred and approximated costs for outpatient scans (CMS Resource-Based Relative Value Scale—based reimbursement amount).

The MR examinations were assumed to use 45-minute time slots. The actual scan time for repeat sequences was quantified directly at the scanner console. The base-case cost estimate for a brain MR was \$444.32

(45 minutes), yielding a cost to the hospital of \$592 per hour (\$9.87 per minute). This parameter value was used to estimate the expense of repeat sequences associated with motion artifacts. For simplification, additional costs, such as nonradiology nursing time (which varies with the patient's level of acuity), transport, sedation, and gadolinium administration were not included. We applied univariate sensitivity analysis to the hourly base-case cost scenario (20% higher/lower) to provide a range of financial implications, with a lower bound of \$474 and an upper bound of \$711.

RESULTS

During the week-long sample period, 207 MRI examinations were attempted, including 3 failed examinations for which no images were acquired. Two failed because of severe motion and/or lack of patient cooperation; 1 failed owing to technical reasons. The lost time could not be accounted for in these failed examinations and thus were excluded from our tally. The remaining 204 examinations sent to PACS comprised 54.6% of OP and 45.4% of IP and/or ED examinations and totaled 1,238 attempted and/or completed sequences. Of these, 12 examinations of the abdomen and/or pelvis were evaluated and found to have significant respiratory and/or cardiac motion that precluded assessment for gross patient motion; these were excluded.

The remaining 192 examinations (women:men = 97:95; patient age range: 21-87 years; mean age: 56 years; 118 OP and 76 IP and/or ED examinations) contained 68 repeat sequences in 38 patients (representing a prevalence

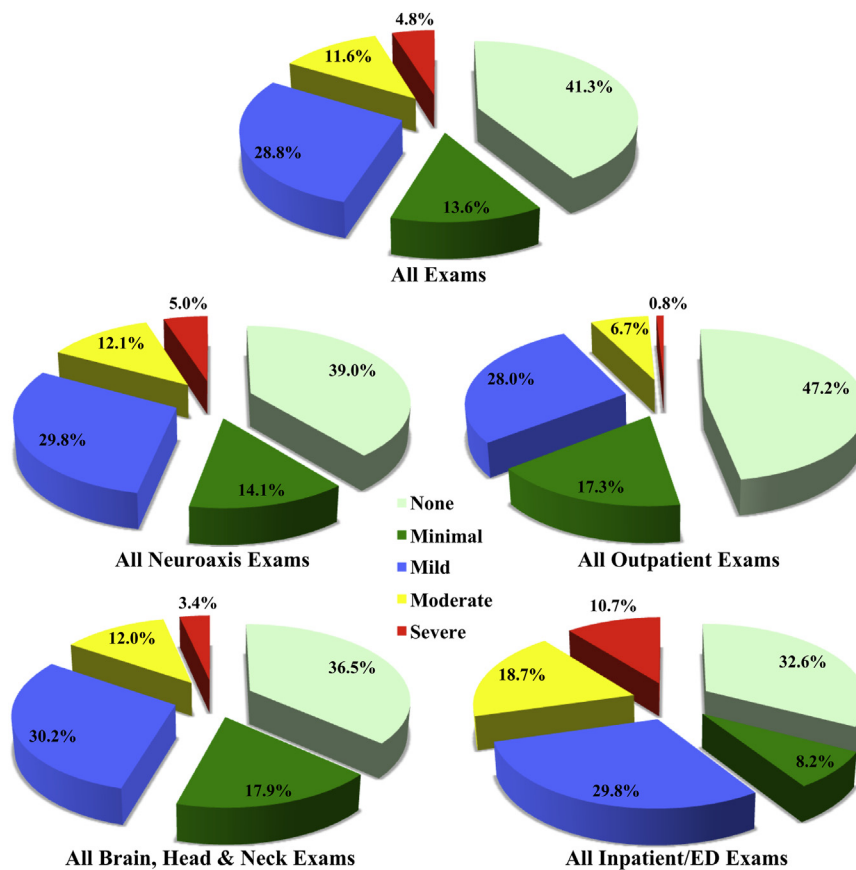


Fig 1. Graphical representation of the prevalence and distribution of motion artifacts during the consensus evaluation. The subjective assessment of motion based on the extent of assessed motion artifacts is depicted as a percentage, delineated by the anatomy imaged in examinations (comprised of “All Exams,” the subset of “Neuroaxis Exams,” and the subset of “Brain, Head and Neck Exams”) and patient disposition (“Outpatient” versus “Inpatient/ED”). The color scale delineates the extent of motion artifacts (none, minimal, mild, moderate, and severe), based on the consensus evaluation. ED = emergency department.

of 19.8% for all completed MRI examinations). These 192 examinations contained 203 sequences (including repeated sequences) with moderate and/or severe motion artifact, and thus of suboptimal quality. Of the 1,238 attempted and/or completed sequences, 727 (58.7%) were found to have at least minimal motion artifacts by visual inspection.

A quantitative summary of the prevalence of motion artifacts is provided in Figure 1, based on imaged anatomy (across all 192 examinations, 173 or 90.1% were limited to the neuroaxis, and 120 or 62.5% were limited to the brain, and the head and neck region) and patient disposition (OP versus IP and/or ED examinations). The mean prevalence of motion artifacts is provided on a per-examination basis in Figure 2, which is similarly based on imaged anatomy and patient disposition.

The 68 repeat sequences required 278.5 minutes of additional scan time to acquire (averaging 4 minutes, 10 seconds per sequence). Base-case cost estimates applied to

additional sequence time, using the average base-case MR cost to the hospital of \$592 per hour (\$9.87 per minute), yielded \$2,750 per week of forgone institution revenue in attempting to correct for patient motion artifacts related to repeat sequences alone. Annually, this amount could imply >\$140,000 per year in forgone hospital revenue and/or additional costs incurred, depending on the patient mix of IP, OP, and ED patients and reimbursement scenarios. Our sensitivity analysis resulted in a lower-bound nonreimbursed cost estimate of \$114,000, and an upper bound of \$172,000. For the cumulative 203 sequences that were found to contain moderate and/or severe motion artifacts (including potentially repeated sequences), this amount would represent an expense of approximately \$8,351 per week (\$434,000 per year) to correct for motion artifacts that rendered acquired images nondiagnostic for clinical evaluation (annual lower and upper bound estimates of \$347,000 and \$521,000, respectively).

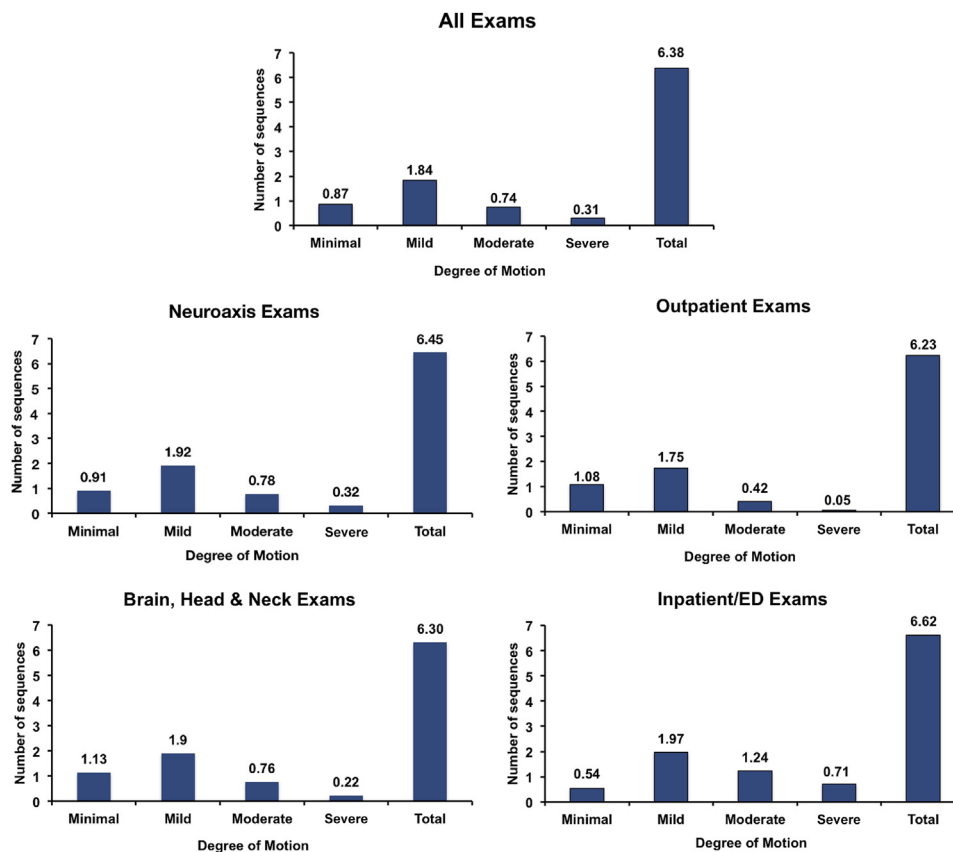


Fig 2. Graphical representation of the mean prevalence and distribution of motion artifacts during the consensus evaluation on a per-examination basis. The relative degree of motion artifact is depicted along the x-axis as the mean incidence and extent of motion artifacts on a per-examination basis; “Total” represents the mean number of completed sequences performed per examination. Examinations are separated based on the anatomy imaged in examinations (comprised of “All Exams,” the subset of “Neuroaxis Exams,” and the subset of “Brain, Head and Neck Exams”) and patient disposition (“Outpatient” versus “Inpatient/ED”). The degree of motion artifact was assessed by consensus, as in [Figure 1](#) (none, minimal, mild, moderate, and severe). ED = emergency department.

When we separately evaluated imaging of the brain, and the head and neck region (including MR angiography, but excluding examinations of the cervical spine), 117 completed (including potentially repeated) sequences in 120 examinations were assessed as moderately or severely motion-artifact degraded. In total, 57.6% of all moderately or severely motion-artifact degraded sequences were MR examinations of the brain, and the head and neck region, and these alone represented an estimated institutional opportunity cost of \$4,809 per week (\$250,000 per year; with a lower bound of \$200,000, and an upper bound of \$300,000). The axial postcontrast T1-weighted sequence was the most commonly repeated sequence, repeated in 4 of the 38 patients with repeated sequences (10.5% prevalence).

DISCUSSION

Patient motion represents a formidable challenge that affects much of the global MR community, resulting in

throughput delays, inefficiencies in use of hospital resources, and potentially suboptimal radiologic interpretations. The prevalence of repeated sequences may vary from week to week, but our results suggest that the prevalence approaches 20% of all MRI examinations (similar to the 16.6% prevalence identified in a preliminary study [17]). Compared with this earlier study [17], the current study offers an improved measure of the prevalence of motion artifacts and associated image degradation, as rejected examinations were better captured in this study. In addition, the scale used to assess all examinations included the potential for clinical impact in image interpretation, and we believe it represents an improved metric in the subjective quantification of motion artifacts.

Using this scale, we estimated that the radiology-specific institutional costs associated with patient motion are likely >\$115,000 per scanner per year (lower bound: \$92,600; upper bound: \$139,000), indicating substantial

implications to the finance and efficiency of high-volume multiscanner hospitals. Therefore, investing in research and software packages that correct for motion in MR examinations is advantageous for institutions, since they would likely lessen patient and provider burden and positively enhance workflow and throughput. In addition, efforts should be made to further reduce sequence acquisition time.

The decision to include moderate and severe examinations as a lost-opportunity cost to the hospital is based on the observation that acquisition of these sequences represents scan time expended on acquisition of non-diagnostic information (ie, time spent without the desired outcome). The relative proportion of examinations with moderate or severe motion degradation in our evaluation was similar to that reported in a prior quantitative study [18].

Our results suggest that the imaged body part is less critical than other factors in predicting patient motion. Specifically, exclusion of the 19 examinations of the musculoskeletal system did not significantly alter the relative prevalence and distribution of motion artifacts during the consensus evaluation (please note comparison of “All Exams” versus the subset of “Neuroaxis Exams,” in Figs. 1 and 2). However, patient disposition (whether the patient is imaged as an outpatient or an IP and/or ED patient) did significantly alter the relative prevalence and distribution of motion artifacts, possibly because of inherent differences between respective patient populations (OPs are presumably healthier and in less acute distress relative to IP and/or ED patients, who are typically in mild, if not substantial, distress and pain during imaging).

A precise estimate of direct and indirect costs associated with motion artifacts is difficult to make, particularly with the complex IP and OP distinctions in US health care systems. Adding to this challenge is geographic variability in reimbursement, payer-mix variability, limited cost transparency, variability in sedation requirements, and in-hospital referral and practice patterns. We used a simplified, averaged-cost approach to estimate cost implications for patient motion during “MRI, brain without contrast.”

A few parameters were not included in our estimates, but may affect the cost of MR examinations. These include: the burden to the current and waiting patients, workflow impediments associated with the additional time needed to query patients about motion and to reinforce the need to lie still, the time lost as a result of attempted, but failed, sequences and/or examinations, and the time lost to place such patients in the scanner. Scan interruptions for repeated

requests for patients to remain motionless are difficult to quantify and were not captured during this study.

In addition, the clinical indication for patient sedation is multifactorial and may include the anticipation of patient motion. In this context, sedation may frequently be used to prospectively reduce patient motion (particularly in pediatric imaging), which can increase motion-related imaging costs and expose patients to the risks of sedation. However, examinations requiring sedation for motion control were not differentiated in our study design, and thus the time requirements for sedation and the added cost to reduce motion artifacts by virtue of patient sedation were not included in our cost estimate. Furthermore, the potential medicolegal risk of interpreting motion-degraded images, as it pertains to patient safety, is a critical point to recognize. Finally, the number of patients asked to return to repeat a sequence and/or examination was not captured by this study design; thus, the associated opportunity cost of these repeated examinations was potentially underestimated.

The retrospective nature of this study, the small sample size, and the short duration are acknowledged limitations. Additionally, the patient population evaluated in our study may not reflect that of other institutions and imaging centers, given that notable differences were found in the prevalence of significant motion artifacts between sequences related to OP (7.5%) versus IP and/or ED (29.4%) examinations. However, we believe that despite these imperfections, the estimated financial impact resulting from motion artifacts and repeat sequences represents a substantial, nonreimbursed institutional opportunity cost.

Our sensitivity analysis provides a range of expectations regarding revenue and cost. Elimination of wasted effort and unnecessary work is increasingly important in “learning health systems” [19] that are experiencing declining reimbursement policies for imaging services as part of the general trend toward containing the cost of US (and global) health care. The results of this study suggest that the goal of reducing motion artifacts, and the related image degradation, represents an opportunity to improve efficiency, reduce costs, and improve imaging services.

The current study evaluated the prevalence of motion artifacts using a quantitative clinical scale, and explored the associated radiology-specific cost estimates of patient motion from a hospital perspective. Future work might include a similar evaluation over a longer time period, with inclusion of additional imaging centers, a larger and less-homogeneous patient population,

and correlation of the developed clinical scale with quantitative imaging metrics, such as those previously proposed [20]. A deeper understanding of the baseline prevalence of motion artifacts would allow for improved assessment of the potential benefits derived from incorporating various motion-correction techniques (including, but not limited to, those previously proposed [8-16]). Finally, a more detailed and precise cost estimate (such as the time-based assessment proposed by Kaplan and Anderson [21]) can be obtained by correlating the exact method(s) of reimbursement and/or internal cost structures and time spent on care, with the specific imaged part of the anatomy and patient disposition (IP, ED, or OP) providing better guidance regarding implemented motion-correction techniques and improved hospital efficiencies.

TAKE-HOME POINTS

- Patient motion is costly, whether measured directly from repeated sequences (occurring in approximately 20% of MR examinations) or from those that should have been repeated (16.4% of all *attempted sequences*). These costs may affect much of the global MR community, reducing resource efficiency and the quality of patient care.
- Motion artifacts represent a frequent cause of MR image degradation, affecting up to 15.3% of head and/or brain MR sequences at our institution (similar to the rate in a prior report [1]), and can result in frequently repeated sequences (affecting 19.8% of examinations in the current study).
- Our analysis suggests that the cost implications of motion artifacts can approach \$115,000 per scanner per year, and that the goal of reducing motion artifacts through improved imaging strategies represents an opportunity to improve the quality and safety of MR imaging services, ultimately improving health care efficiency.
- Additional stakeholder investment is needed by hospitals, researchers, and manufacturers to improve patient-centered care processes.

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