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EDITORIAL

Roentgen stereophotogrammetric analysis: still a very valuable tool in the orthopaedic research armamentarium

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Cite this article: *Bone Joint Res* 2022;11(4):210–213.

Keywords: Radiostereometric analysis, Cementless implants, Stem migration

Roentgen stereophotogrammetric analysis (RSA) was first introduced by Selvik in 1974 to assess implant micromotion.[1] The standard RSA setup involves two synchronous X-ray tubes directed at a 20° angle relative to the normal vector, and a calibration plate positioned underneath the table. The calibration box contains reference markers to define the coordinates and standardize the position of the foci.[2]

Traditionally, the analysis entailed the reconstruction of a 3D position of the implant, based on markers (usually tantalum beads) attached to the implant and surrounding bone. The marker-based analysis is characterized by high accuracy and precision, although the integration of tantalum markers on the implant became a matter of concern, particularly as it could generate local stress risers. To overcome this, the concept of model-based RSA was introduced, whereby inert tantalum beads are inserted into the bone around the prosthesis. These act as fixed reference points from which the spatial resolution and rotation of the implant can be calculated, averting the need to attach markers to the implant.[2,3] Subsequently, the implant silhouette detected by the RSA radiograph is matched to a virtual 3D model of the prosthesis obtained from the manufacturer or via reverse engineering.[2]

RSA has been widely used in the assessment of implant stability and survivorship in joint arthroplasty, with the evaluation of biological fixation and implant migration used as a surrogate for survivorship.[4–7] The importance of implant survival is paramount; hence there is growing interest in elucidating how RSA migration analysis relates to long-term stability and clinically meaningful outcomes, e.g. aseptic loosening and revision. Reports have suggested that early micromotion can be predictive of mechanical loosening and failure.[8–10] These observations are corroborated by an important study that reported a strong correlation between the two-year migration evidenced by RSA and long-term fixation, suggesting the suitability of early RSA results as a surrogate for long-term fixation.[11]

A potential advantage of cementless implants is that they can achieve better osseointegration, by replicating the elasticity and mechanical properties of trabecular bone.[12,13] Recently, two-year results of implant migration were reported between a novel, cruciate-retaining cementless 3D-printed total knee arthroplasty (TKA) compared with a similarly designed cemented TKA. The authors established that cementless implants exhibited more migration than cemented prostheses two years postoperatively.[6] However, we must recognize that migration is implant-dependent and behaviour should be scrutinized individually. Pooling RSA data of cementless and cemented implants is not methodologically sound. In their analysis of the implant migration of three cemented and five cementless designs, Laende et al[14] found that different migration patterns were evident with different methods of fixation. Furthermore, the higher initial migration during the first year, commonly observed with cementless implants, has not been linked to inferior long-term fixation. This could be due to an initial 'settling' phase, during which bone growth and osseointegration are achieved. Following this period, cementless implants have displayed great stability[15] and excellent survivorship,[16,17] while cemented tibial components are still at risk of debonding at the cement-implant interface, cement delamination, and other cement-related complications. Consequently, we need to revisit the acceptable RSA migration thresholds in cemented and cementless TKA.

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doi: 10.1302/2046-3758.114.BJR-2021-0593.R1

Bone Joint Res 2022;11(4):210–213.

RSA remains a valuable tool in the research armamentarium, with RSA data interpreted along with other radiological, surgical, and patient-centred outcomes.[18–20] Over the last decade, the arthroplasty world has witnessed a growth in new implant designs, such as the ATTUNE prosthesis, aimed at improving patellofemoral kinematics and mid-flexion stability. A key study using model-based RSA compared migration, and clinical and patient-reported outcomes, between the ATTUNE design and PFC-sigma design.[21] The authors reported comparable tibial component migration at two years, but with more radiolucent lines observed at the implant-cement interface with the ATTUNE design, reinforcing that additional radiological parameters should be considered. Moreover, we need to be attentive to the failure mode, as there are exceptions in the behaviour of each implant. A recent paper studying clinical outcomes of the ATTUNE TKA design revealed a revision rate of 11.5%, the majority of which was attributed to debonding of the tibial component.[22] Thus, RSA is a very useful marker, but cannot be used as the sole indicator of an implant's longevity.

Recently, we have seen proponents of asymmetrical tibial baseplate designs, highlighting the most precise anatomical match to the proximal tibia. Koster et al[23] published the two-year results of a randomized controlled trial (RCT) comparing the migration of an asymmetrical and symmetrical tibial design in TKA. In 69 patients, they found comparable migration with reference to the maximum total point motion (MTPM), suggesting a similar anticipated aseptic loosening risk. However, to adjudicate longevity and fixation, additional parameters such as tibial coverage should be examined. Maximizing tibial coverage is critical to avoiding malrotation, flexion-extension gap mismatch, and patellar maltracking.[24] It has also been postulated to result in improved load transfer to the proximal tibia and, conceptually, greater fixation.[25] In light of early reports suggesting an inferior tibial plateau coverage with asymmetrical baseplates,[26] the need to interpret RSA data alongside other radiological and surgical parameters is imperative. Furthermore, there has been a sharp increase in the percentage of younger patients undergoing total hip arthroplasty (THA).[27] The desire for short stems, bone preservation, and better load-transfer has paralleled the altering demographics of THA.[27] The role of RSA has once again been vital in assessing micromotion and adjudicating the safety of these designs.[4,21,28]

Other potential applications of RSA include in vivo linear and volumetric wear using model-based radiostereometric analysis.[29–33] Gascoyne et al[30] used model-based RSA to evaluate linear and volumetric polyethylene (PE) wear in 101 TKA patients. Consecutive, precise measurements of joint space distance in supine and weightbearing positions were used as a surrogate for determining linear polyethylene (PE) wear, while volumetric wear was measured following the introduction of the computer-aided design (CAD) model and assessment of the degree of overlap between the PE component and femoral condyles.[30] Similarly, RSA was used in another study to measure the in vivo wear of different bearing types of the Oxford unicompartmental knee replacement. The linear distance between the tibial tray and femoral prosthesis was calculated and subtracted from the estimated bearing thickness.[31]

We have seen RSA used in lengthening osteotomy studies,[34] to monitor fracture healing and stability,[35,36] in spinal fusion,[37] and for soft-tissue biomechanics studies in anterior cruciate ligament (ACL) reconstruction[38] and rotator cuff repair.[39] The application of RSA in monitoring fracture-healing can provide invaluable information concerning interfragmentary micromotion[40] and the exact time of union.[41] Amalgamating morphological features and information pertaining to fracture line distribution[42] with RSA migration data could be used as a tool to inform decision-making and risk stratification.[41]

Besides static analyses, RSA can be used to obtain dynamic views and assess joint kinematics.[43] Dynamic assessment (dRSA) can generate valuable data following TKA in relation to kinematics of various prostheses designs. We have seen dRSA studies comparing the restoration of native knee joint kinematics and joint laxity after ACL reconstruction.[44] Furthermore, combination with CT or MRI offers a potentially more precise insight into implant stability and wear. We have also witnessed attempts to identify bony landmarks and monitor implant migration using low-dose CT image segmentation.[45] Generating 3D data and employing fusion algorithms may even render the use of RSA beads unnecessary in the future.[46] The leap from RSA to CT migration analysis would be a paradigm shift for migration measurement, but requires careful development and evaluation.

Another advantage we have seen with RSA is the relatively small sample size to achieve adequate power. Owing to its high accuracy, it has been well documented as part of the stepwise introduction of new implants by Malchau et al,[47] advocating a small prospective RCT using RSA as the primary endpoint following preclinical testing. In relation to sample size, the majority of published studies report that a two-arm RCT with 25 to 30 patients per group is adequate to achieve power of 80% to 90%.[6,48] However, a methodological consideration with model-based RSA is that precision values are applicable to the specific component design. For this reason, it is recommended that a phantom experiment should be performed prior to a clinical RSA study to establish the lower precision limits of the model for the particular prosthesis.[2]

Advances in arthroplasty have led to the development of new technologies, from 3D printing to patient-specific instrumentation and robotics,[49] and RSA can be used to facilitate their safe introduction and implementation. Improving the accessibility of RSA and facilitating its adoption beyond clinical trials is key. Often, one of the potential barriers with the conventional RSA setup is the need to obtain specialized RSA radiographs besides standard anteroposterior and lateral views. To that end, there are reports in hip and knee arthroplasty describing modified approaches using standard clinical radiographs to perform RSA.[50,51] The research agenda should now focus on standardizing a validated protocol and modified setup, enabling standard clinical radiological views to be used for RSA migration analysis. This will reduce barriers and facilitate the recruitment and monitoring of implants on a larger scale.

Increasing importance is placed on addressing unanswered research questions identified by patients, healthcare professionals, and other key stakeholders.[12,52] In the UK and Europe, the key is to harmonize data collection with the rigour and regulatory requirements mandated by the Medical Device Regulation.[53] As reflected in the British Orthopaedic Association's statement, costly, long-term studies may not be commercially viable, and could lead to an increase in the cost of implants, both for 'state of the art' and existing devices. From that perspective, RSA should be a key pillar of introducing new implants and providing robust post-marketing surveillance.

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Funding statement:
- The authors disclose receipt of the following financial or material support for the research, authorship, and/or publication of this article: this scientific paper was supported by the Onassis Foundation - Scholarship ID: F ZR 065-1/2021-2022.