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Targeted four-dimensional computerized tomography scans for elbow disorders: a literature review and refinement of existing technique with two exemplar cases

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A R T I C L E I N F O

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Background: Four-dimensional computerized tomographies (4D-CTs) or motion CTs in elbow disorders have several potential advantages over conventional static imaging such as a reduction of misdiagnoses, a more targeted surgical approach, better patient understanding of their condition and potentially faster operative times. However, the radiation dose is higher than conventional static CT scans so this should be used judiciously. Our study reviews the current literature for 4D-CTs in dynamic elbow disorders and provides a technical note describing radiation-reduced targeted elbow 4D-CTs (te4D-CT) with two exemplar cases alongside our recommendations for when te4D-CTs are indicated.
Methods: te4D-CTs are performed in a lateral decubitus elbow above head position. Preliminary static source axial cut CT obtained with subsequent sagittal and axial planes reconstruction and 3D reconstruction obtained, followed by scan performed in motion and reconstructed to 4D Component. te4D-CTs are taken for either flexion and extension (FE) or pronation and supination (PS) motions depending on the clinical pathology suspected following thorough clinical examination.
Results: te4D-CT for PS and FE protocol scans had an effective radiation exposure dose of 0.53 and 0.95mSv, respectively, compared to 1.13-1.83 mSv in conventional elbow 4D-CTs. In addition, te4D-CTs have good diagnostic accuracy provided that the FE or PS pathology is identified carefully by the ordering physician.
Conclusion: te4D-CT using isolated pronation and supination, or flexion and extension protocols does come with a significantly reduced radiation dose and can be of equal clinical yield compared with 4D-CTs.
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Four-dimensional computerized tomography (4D-CT) is defined as a three-dimensional computerized tomography volume which is imaged over a time which generates a dynamic volume set.[11] 4D-CT was developed in the early 2000s and since then has garnered large amounts of interest in view of its ability to review anatomical parts in motion.[17] It has been shown to be particularly useful in the field of orthopedics for dynamic disorders in the elbow and wrist joints, patella maltracking and snapping scapula syndrome amongst other various musculoskeletal conditions.[2,4,13,16,18,23]

Elbow 4D-CTs (e4D-CT) have several potential advantages over conventional static imaging such as a reduction of misdiagnoses, more targeted surgical approach, faster operative times and better patient understanding and its use should be considered in the diagnosis and preoperative planning for select dynamic elbow disorders after careful clinical examination.[14,18] The diagnosis of dynamic elbow disorders conventionally has relied largely upon clinical findings and correlation with plain radiographs, static computerized tomography (CT) and Magnetic Resonance Imaging (MRI) scans. Diagnostic arthroscopy may also be used but it is an

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invasive procedure. Whilst static imaging such as CT and MRI scans provides a significant amount of information, it has limited uses in delineating dynamic elbow pathologies. Specifically in elbow pathologies, a study found a potential misdiagnosis rate of >50% when comparing conventional static images with e4D-CT diagnosed conditions.[18] With a more specific and assured diagnosis, surgeons are able to plan and execute surgeries with a more targeted approach which may minimise skin incisions, reduce operating time, and thus potentially reduce infection risk.[5,20] Last but not least, with e4D-CTs informed consent can be taken to the next level with better illustrations to patients whilst giving surgeons the ability to counsel on a more specific procedure type.

The radiation dose in 4D-CT is higher than conventional CT scans. Radiation dose for e4D-CTs with an arm above the head technique have reported rates of 1.13-1.83 mSv compared to a conventional above the head elbow CT of 0.21 mSv or a whole-body CT of ~10 mSv.[7,9,10,18,19] For context, the average resident in the United states of America is exposed to approximately 3 mSv annually.[1] Current evidence suggests doses between 5 and 125 mSv may cause a small but statistically significant increase in cancer risk.[3] Acknowledging higher radiation doses in e4D-CTs, we have attempted to minimize this through targeted motion protocols of the elbow in either flexion-extension (FE) or pronation-supination (PS).

This study provides a technical note describing radiation-reduced targeted elbow 4D-CTs (te4D-CT) with two exemplar cases alongside our recommendations for when te4D-CTs are indicated alongside a review of the current literature for 4D-CTs in elbow disorders.

Materials and methods

This technique will cover the use of te4D-CTs in select elbow pathologies, where the pathology is predominantly an issue with FE or PS. This is a refinement of the initial technique described by the principal author where patients underwent the full 4D-CT scan protocol.

Patients are first reviewed clinically to determine the type of elbow disorder they may have, which may be broadly categorized as 1) Flexion Extension (FE), 2) Pronation Supination (PS) or 3) Mixed Dynamic Disorders. Only patients with isolated FE or PS dynamic elbow disorders should be considered for te4D-CT.

The protocol used was similar to the original protocol described by the principal author, except with a targeted approach. The scanner utilized was a Siemens Force Dual Source CT (Erlangen, Germany). Prior to commencement of the scan, patients practiced moving through maximum range of motion (ROM) for FE or PS, as directed by the lead radiographer. Patients were positioned in a lateral decubitus position with their elbow above their head and support with sandbags to reduce unwanted movement.

A preliminary standard CT images were obtained with the volume range set to 5.8 cm and slice thickness and interval being set at 0.6 mm and 0.5 mm using bone and soft tissue software algorithms. 3D images were subsequently reconstructed. Following this, the te4D-CT was performed using similar slice thickness and interval between slices. For PS protocol, full ranges of pronation and supination in maximal extension and at 45° flexion were completed. Settings were set at 80 kV tube voltage, 0.25 s gantry rotation time, 90 mA current and continuous x-ray. Each motion cycle was set to 15 seconds. For the FE protocol, flexion and extension was performed with forearm in neutral pronation/supination. An exception to this can be considered if the specific block to FE occurred in either pronation or supination. Settings were kept exactly the same as PS protocol for simplification purposes. The source data was subsequently reconstructed to 4D images with each image taken at 0.25 second intervals which gave us approximately 60 data sets per motion cycle.

Effective radiation dose was calculated by the dose length product multiplied by the organ specific conversion factor of 0.0008 for an above the elbow CT.[10] te4D-CT for PS and FE protocol scans had an approximate effective radiation exposure dose of 0.53 and 0.95 mSv, respectively. This is compared to the originally described e4D-CTs which have reported radiation exposures of 1.13-1.83 mSv.[7,18]

Results

Exemplar case 1 of flexion and extension elbow disorder

A 40-year-old male was reviewed in clinic for a 6-month history of atraumatic mechanical right elbow pain. During his clinic review, he had restricted ROM in flexion and extension (F/E) and goniometer measurements showed ROM of 40-110 in both pronation and supination, with pain at the terminal motion of flexion and extension. Plain radiographs showed degenerative changes primarily in the ulnar-humeral joint, with prominent osteophytes at the coronoid and olecranon tip (Fig. 1). Given the isolated flexion/extension restriction alongside plain radiographic features of ulnar-humeral osteoarthritis and an unremarkable appearance of the radio-humeral joint, a te4DCT was conducted, which revealed impingement caused by the two

Figure 1 Case 1: Preoperative plain elbow radiographs (anterior-posterior and lateral).

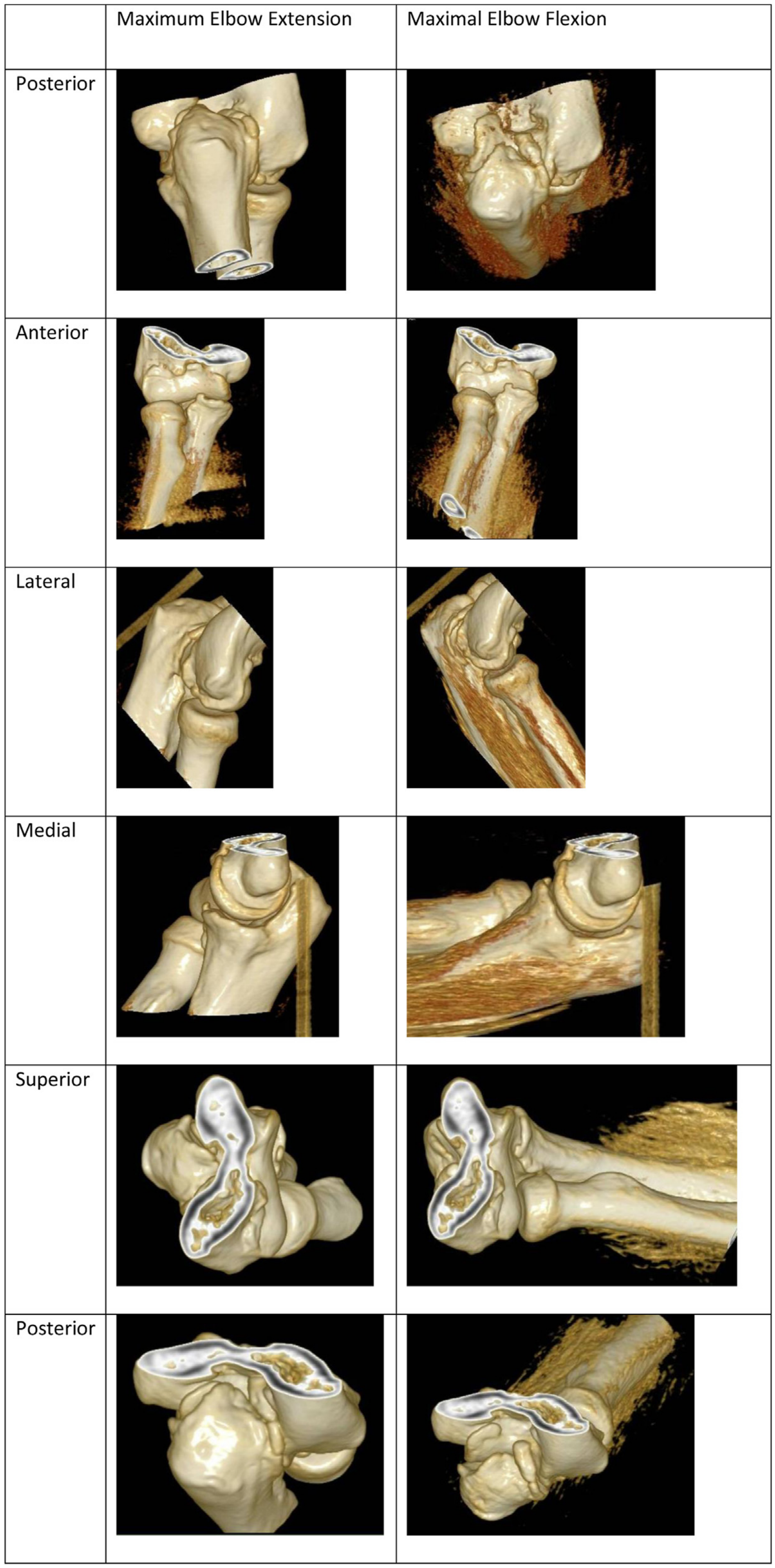

Figure 2 Case 1: te4D-CTs in an isolated flexion/extension pathology.

prominent osteophytes on the coronoid tip and the posterior aspect of the olecranon, with no intra-articular loose bodies, concomitant joint instability or fractures visualized (Fig. 2). The patient then underwent capsular release and osteophyte débridement of the anterior and posterior osteophytes via a limited lateral column procedure. His postoperative ROM measured at 2 weeks improved to 10-130, and the patient was subsequently given an open-date appointment.

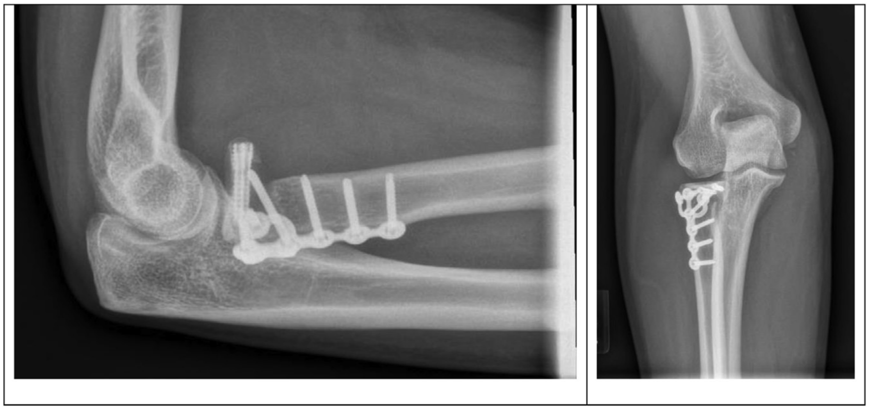

Figure 3 Case 2: Preoperative plain elbow radiographs.

Exemplar case 2 of supination and pronation elbow disorder

A 37-year-old male, with a history of surgical fixation of right radial head fracture 4 months ago, presented with restricted pronation/supination ROM of the right elbow and pain at terminal supination. Despite strict compliance with rehabilitative exercises as guided by institutional physiotherapists, the symptoms persisted. Plain radiographs demonstrated no breach of the implants into the joint line and no evidence of malunion or nonunion of the previous radial head fracture (Fig. 3). In view of this patient's isolated pronation/supination pathology, a decision was made to perform a te4D-CT to confirm the cause of his symptoms. A te4D-CT with an isolated PS protocol was conducted, which showed impingement of the radial plate onto the ulna at terminal supination with no evidence of osteophyte prominence, loose bodies, or other mechanical block that could account for his clinical presentation (Fig. 4). He underwent removal of right radial head implants and he subsequently achieved full concentric ROM in pronation and supination 4 months after implant removal.

Discussion

The current published literature on 4D-CTs in elbow pathologies is highly limited, with few studies having reviewed their usage. Goh and Lau described the first case of e4D-CT usage in 2012 for post-traumatic ulnar-humeral osteoarthritis.[7] Yamamoto et al[24] (2016) further explored this in a 10-patient case series, where a 4D simulation model was created using 3D CT scans and Mimics software preoperatively to identify points of impingement. Their patients subsequently underwent débridement arthroplasty for their primary elbow osteoarthritis successfully. Miyake et al (2016) similarly used a e4D-CTs as a planning tool for targeted arthroscopic osteophyte débridement in a case series of 20 patients and reported significant postoperative improvement in ROM. More recently, in a retrospective study of 28 cases comparing between e4D-CTs and conventional imaging showed a potential misdiagnosis rate of over 50% when using conventional imaging techniques. Within the study, there were 5 cases of suspected posterolateral rotatory instability but e4D-CTs demonstrated a stable elbow joint in 3 cases.[18] However despite the benefit of improved diagnostic accuracy of 4D-CTs a few issues have prevented widespread adoption such as the requirement for specialized software, specially trained radiographers, the time taken per scan, alongside the concerns of a higher radiation dose.

The indications for e4D-CTs have not been clearly defined in the literature and its usage is usually governed by the clinician's certainty of a dynamic pathology, of which 4D-CTs can be used in complex cases or where multiple differentials are likely or possible. Some published indications for 4D-CTs include dynamic instability/joint subluxation, distal biceps tendinosis, impingement or partial tears primary or secondary osteoarthritis with loose bodies or impingement osteophytes, fracture malunion, complex elbow disorders like hemimelia or decreased ROM after surgery with suspected implant impingement.[7,12,18] In our experience, many of these cases tend to present primarily with dynamic flexion/extension or pronation/supination issues and hence for these select cases te4D-CTs may be appropriate. However, in cases of which diagnoses are uncertain or if a mixed FE and PS disorder is suspected a full 4D-CT may be more appropriate.

4D-CT imaging can also improve the understanding of dynamic elbow disorders. eg, in cases of failed débridement arthroplasty for primary elbow osteoarthritis, 4D-CTs have identified concurrent radial head instability as a contributing factor to the persistent symptoms after surgery.[15,18] There has also been advancement in other musculoskeletal conditions such as ankle instability, patella instability and wrist motions and kinematics.[6,8,21] Biomechanical studies of elbow anatomy complemented with 4D-CTs may improve our understanding of this complex joint and further our understanding of elbow pathologies.

The two key challenges in elbow 4D-CTs are radiation exposure and its time-consuming nature against conventional CT scans which te4D-CTs sought to address. By limiting the scan to a single motion of PS or FE after careful clinical examination, we are able to not only reduce radiation exposure, but patients are only required to learn the motion sequence for a single motion which can reduce time and burden for imaging departments. Our te4D-CT for PS and FE protocol scans had an approximate effective radiation exposure dose of 0.53 and 0.95 mSv, respectively. In comparison, above the head elbow 4D-CTs have approximate radiation exposure doses of 1.13-1.83 mSv and above the head elbow conventional CTs of approximately 0.21 mSv based on current literature.[7,10,18] For context in regards to activities of daily living, radiation doses from te4D-CTs (0.1-1.0 mSv) are approximately equivalent to a flight of 4500 miles, vs. e4D-CTs (>1 mSv) which carry a slightly higher radiation risk comparable to driving 2000 miles.[22] With multimorbid patients being an ever-growing population, there is certainly a need to minimize radiation especially in patients who require multiple scans for various pathologies. Equipped with this new technique and knowledge we can educate and reassure patients regarding the risks of te4D-CTs particularly with patients who have concerns over the potential carcinogenic effects associated with radiation with the use of CT scans.

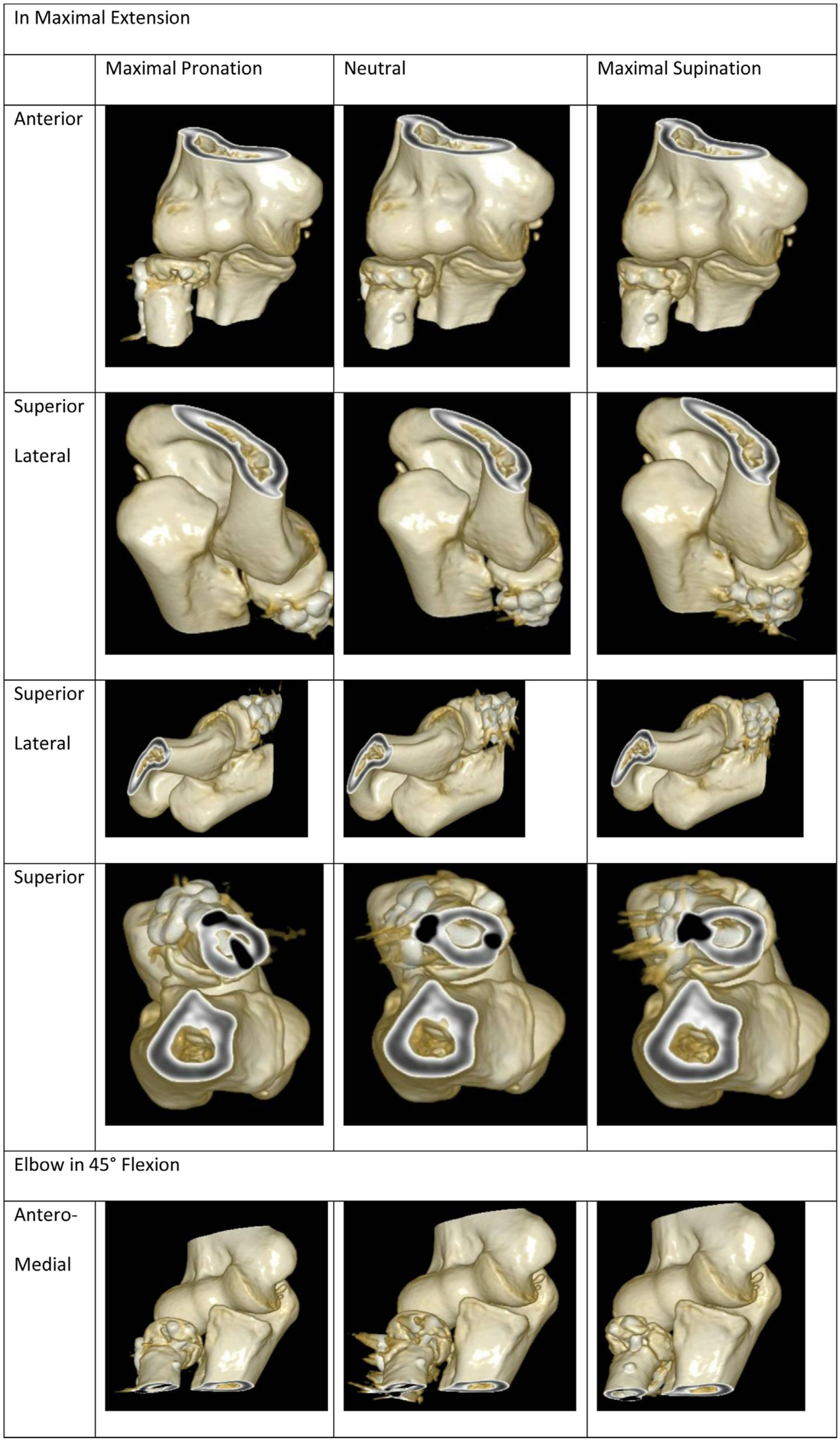

Figure 4 Case 2: te4D-CTs in an isolated pronation/supination pathology.

Limitations

Although our study provides valuable insights, it has some limitations. Firstly, our quoted exposure for radiation doses for te4D-CTs is based off the two exemplar cases done in our institution and compared against e4D-CT radiation doses cited in current literature. We acknowledge that radiation doses may be multifactorial and can differ based on CT scanner, radiographer training and institution protocols. Secondly this study does not directly compare the outcomes of te4D-CT against 4D-CT especially regarding rate of misdiagnosis and as such is difficult to comment on its safety and efficacy and further studies may be warranted to compare the two. Lastly, even though no additional costs were imposed on the patient for this study, we expect te4D-CT scans to have a higher cost as compared to 3D CT scans as the duration of the scans are longer.

Conclusion

The utilization of 4D-CTs in elbow pathologies has been reported in current literature to decrease the rate of misdiagnoses. This technology in theory enables physicians to have more accurate preoperative planning and can bring informed consent and display of information to patients to a level that conventional static imaging or plastic models may struggle to achieve. te4D-CTs in the appropriate patient can be as effective as e4D-CTs in the diagnosis of dynamic elbow pathologies with a significantly lower radiation dose. However, further clinical studies to compare the two protocols may be warranted.

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