

Radial Head Replacement

Overview

- Radial head replacement is a reasonable option for patients with comminuted radial head fractures and complex elbow trauma [2].
- Radial head replacement is recommended for comminuted fractures with satisfactory medium- and long-term results [13].
- Bipolar-cemented implants show lower revision rates compared to other types in radial head replacement [13].
- Better outcomes are reported for radial head arthroplasty compared to radial head excision in terms of elbow stability, range of motion, pain, and fewer complications [7].
- The intraoperative decision to fix or replace the radial head is critical to optimize treatment outcomes [4].
- Adequate knowledge of surgical indications, types of implants, and surgical technique is essential for a satisfactory outcome when using a radial head prosthesis for nonreconstructable radial head fractures [10].
- Implant fixation type does not appear to affect functional outcomes of radial head arthroplasty [5].
- Midterm outcomes of the EVOLVE radial head prosthesis are satisfactory with low associated complication rates [6].
- Overlengthening of the radial column is a complication of radial head replacement that requires identification and treatment [1].
- The preferred treatment for failed radial head arthroplasty depends mainly on the chondral condition and stability of the elbow joint [12].
- Reproducibility of results in radial head arthroplasty studies would be improved by using a minimum follow-up of three years [3].
- A consensus definition of the reasons for failure after radial head arthroplasty is needed to improve result reproducibility [3].

Anatomy & Pathophysiology

- The radial head is disk-shaped and has a greater diameter than the radial neck [41].

- The radial head rotates within the annular ligament [41].
- The radial head has a shallow cuplike surface that articulates with the capitellum proximally [41].
- The flattened articular margin of the radial head articulates with the lesser sigmoid (radial) notch of the ulna [33].
- The nonarticular margin of the radial head comprises about one-third of its diameter and is more rounded and often devoid of cartilage [33].
- The biceps inserts on the radial tuberosity immediately distal to the radial neck [41].
- The radial head is not circular but is somewhat elliptical in shape [33, 45].
- The radiocapitellar dish is elliptical and typically offset from the neck of the radius [33, 45].
- The proximal radius has a slight angulation with respect to the shaft [45].
- The vascular supply to the radial head is provided by branches of the radial recurrent artery and a branch of the ulnar artery, which form a pericervical arterial ring [33].
- A branch of the interosseous artery supports the radial neck [33].
- The nutrient artery provides intraosseous blood supply to the radial head [33].
- The entire radial head is covered with articular cartilage, so its blood supply to the epiphysis is supplied through the more distal metaphysis [41].
- The radial head acts as a secondary restraint to valgus stability of the elbow [17, 25].
- The radial head is an important secondary stabilizer of the elbow [17, 49].
- The posterior interosseous nerve runs deep to the supinator along the lateral aspect of the radial neck [45].
- Full pronation provides an average of approximately 5 cm of safe area for dissection and internal fixation relative to the posterior interosseous nerve [45].
- The nonarticular surface of the radial head is relatively small, with an arc of roughly 90 degrees and its midpoint directly lateral with the arm in neutral position [45].
- The nonarticular area can be identified as the area between the Lister tubercle and the radial styloid on the distal radius [45].
- The “safe zone” for plate placement on the radial head is defined as the nonarticular margin, best identified by positioning the forearm in neutral rotation and placing the plate 10 degrees anterior to the mid-axial line [33].
- The safe zone corresponds to the lateral 100-degree arc with the forearm in neutral rotation [25].
- The safe zone is the arc between the lines drawn through the radial styloid and Lister tubercle [17].
- The stability of the ulnotrochlear articulation is enhanced by interdigitation of a central ridge in the trochlear notch with a groove in the trochlea [45].
- The trochlear notch has separate coronoid and olecranon articular facets with an intervening nonarticular area [45].
- The circumference of the trochlear notch of the ulna is nearly 180 degrees and tilts somewhat posteriorly [45].

- A line drawn between the tips of the olecranon and coronoid processes should create a 30-degree angle with a line parallel to the ulnar shaft [45].
- The radial head plays an important role in load transfer across the elbow [34].

Classification

- Overlengthening of the radial column in radial head replacement is a complication that can be identified and treated using a specific classification system [1].
- Clinical outcome studies indicate that metallic radial head arthroplasty is a reasonable option for patients with comminuted radial head fractures and complex elbow trauma [2].
- Reproducibility of results in radial head arthroplasty studies is improved by using a minimum follow-up of three years combined with a consensus definition of the reasons for failure [3].
- Current data provide no evidence for a specific radial head prosthesis design due to the variety of implant designs and limited evidence [8].
- Anatomic radial head replacement carries a risk of radiographic technical mistakes that correlate to poorer outcomes [9].
- Adequate knowledge of surgical indications, types of implants, and surgical technique is essential for satisfactory outcomes when using a radial head prosthesis for nonreconstructable radial head fractures [10].
- The use of stem auto-expansion as a mode of obtaining primary fixation in radial head arthroplasty appears to be an effective solution for reducing the risk of painful loosening [15].
- For fractures with three or more articular fragments or those not amenable to stable internal fixation, excision of the radial head and prosthetic replacement using monopolar, metallic radial head implants with modular components and a smooth neck is preferred [18].
- Recommendations for surgical treatment of radial head and neck fractures according to the Mason classification are available with the best available evidence [21].
- Mason type 3 radial head fractures treated with open reduction and internal fixation exhibit a higher risk of complications compared to those treated with radial head arthroplasty [24].
- Early mobilization of the elbow is important for the restoration of elbow range of motion and function after management of radial head fractures with elbow dislocation [29].
- Radial head replacement had better elbow function and fewer adverse events than open reduction and internal fixation for Mason type III radial head fractures in the short-term in Chinese populations, although the evidence is of low quality and results may not apply in the longer term or more generally [37].

Clinical Presentation

- Approximately 20% of all elbow fractures involve the radial head [17].
- Radial head fractures can occur in isolation or be associated with more complex injuries such as elbow fractures, dislocations, and soft-tissue injuries [17].

- The radial head functions as a secondary valgus stabilizer of the elbow [17].
- Radial head fractures typically result from a fall on an outstretched hand with the forearm in pronation, resulting in an axial load on the elbow [17].
- 30% of patients with radial head fractures have other soft-tissue and skeletal injuries, including carpal fractures, distal radioulnar joint (DRUJ) injuries, interosseous membrane disruption, coronoid fractures, Monteggia fracture-dislocations, capitellar fractures, and medial or lateral collateral ligament injuries [17].
- Fractures of the radial head typically occur following a fall on an outstretched hand [17].
- Patients should be questioned carefully about concomitant wrist, forearm, or shoulder pain [17].
- Physical examination reveals pain with palpation over the radial head [17].
- Examination should assess elbow range of motion for a block to pronation/supination or flexion/extension [17].
- Examination should assess the forearm, wrist, and elbow for tenderness along the interosseous membrane (Essex-Lopresti lesion), DRUJ instability, medial elbow pain (medial collateral ligament), and lateral elbow pain (lateral collateral ligament) [17].
- Lateral elbow pain and tenderness or limitation in elbow or forearm motion should alert the examiner to the possibility of a radial head fracture [17].
- AP and lateral radiographs of the elbow are routinely obtained for evaluation [17].
- Nondisplaced fractures of the radial head may not be visible on standard radiographs but may be diagnosed by elevation of the anterior and posterior fat pads (the sail sign) due to intra-articular hemarthrosis [17].
- The radiocapitellar view is accomplished by positioning the patient as for a lateral view but angling the tube 45° toward the shoulder [17].
- CT can delineate the location, number, and size of fragments in comminuted fractures and is rapidly emerging as a standard imaging method for complicated radial head fractures [17].
- Aspiration of the intra-articular hematoma and injection of a local anesthetic can be helpful when assessing mechanical blocks to motion [17].
- Most minimally displaced (<3 mm) radial head fractures can be treated nonsurgically if no block to range of motion is present [17].
- Radial head fractures that are significantly displaced, block motion (especially rotation), or are part of more complicated injury patterns are candidates for surgical repair [17].
- Patients with displaced radial head fractures with a block to motion, comminuted fragments, associated elbow instability, or retained intra-articular fragments may benefit from operative intervention [14].
- Patients with a high-energy injury mechanism merit careful evaluation for more complex injury patterns that could potentially be missed [14].
- Most fractures of the radial head are stable and managed non-operatively with good long-term results [11].
- Displaced unstable fractures require restoration of radiocapitellar contact via reconstruction or prosthetic replacement to prevent elbow instability [11].

- Conservative management of isolated Mason II radial head fractures yields favorable therapeutic outcomes with a low incidence of complications [32].
- Recommendations for surgical treatment of radial head and neck fractures according to the Mason classification can now be given with the best available evidence [21].

Investigations

- Radial head fractures account for 15–25% of all elbow fractures [17, 25].
- Of patients with radial head fractures, 30% have other soft-tissue and skeletal injuries [17].
- Associated injuries in radial head fractures include carpal fractures, distal radioulnar joint (DRUJ) injury, interosseous membrane disruption, coronoid fractures, Monteggia fracture-dislocations, capitellar fractures, and medial and lateral collateral ligament injuries [17].
- Displaced radial head fractures with a block to motion, comminuted fragments, associated elbow instability, or retained intra-articular fragments may benefit from operative intervention [13].
- Nondisplaced fractures of the radial head may not be visible on radiographs but may be diagnosed by elevation of the anterior and posterior fat pads (the sail sign) by an intra-articular hemarthrosis [17].
- AP and lateral radiographs of the elbow are routinely obtained for radial head fractures [17].
- For comminuted fractures, CT can delineate the location, number, and size of the fragments and is rapidly emerging as a standard imaging method for more complicated radial head fractures [17].
- Joint aspiration with injection of a local anesthetic can be helpful when assessing mechanical blocks to motion [17].
- The radial head plays an important role as a secondary valgus stabilizer of the elbow [17, 25].
- The ligaments have the most marked influence on elbow stability, particularly when the upper limb is positioned such that valgus and varus gravity loads are applied [20].
- Radial head excision alone is contraindicated in the presence of concomitant ligamentous or bony injury, as doing so will lead to loss of radiocapitellar contact forces and precipitate instability [13].
- Even in the presence of intact collateral ligaments, excision alone has been shown to alter elbow kinematics [13].
- The radial head should not be excised in the presence of extensive damage to primary stabilizers, including MCL (valgus instability), coronoid (posterior instability), interosseous membrane (longitudinal instability), and LCL (posterolateral rotatory instability) [17].
- If radial head excision is to be performed, the push–pull test intraoperatively should have no more than 2 to 4 mm of movement of the radius [13].
- A careful fluoroscopic examination should be performed to rule out any signs of instability before and after radial head excision [13, 16].
- The stability of the elbow and forearm should be evaluated fluoroscopically with varus, valgus, rotational, and axial stress tests before and after radial head excision [16].

- A radial head arthroplasty should be available for use if the elbow is determined to be unstable in any of these planes during excision [16].
- The radial head is an important secondary stabilizer of the elbow; therefore, radial head excision alone is contraindicated in clinical settings in which extensive damage to the primary stabilizers is present [17].

Treatment

NON-OPERATIVE MANAGEMENT

- Nondisplaced and minimally displaced radial head fractures can be treated non-operatively with early mobilization [35].
- Most radial head fractures can be managed nonsurgically with early motion [36].

OPERATIVE INDICATIONS

- Radial head arthroplasty is indicated for displaced unreconstructible fractures larger than one-third of the diameter of the radial head with known or probable medial or lateral collateral ligament or interosseous membrane injury [55].
- Radial head arthroplasty is indicated for nonunion, malunion, and posttraumatic arthritis of the radial head [55].
- Radial head replacement is recommended to help stabilize the joint and facilitate early mobilization in fractures associated with elbow dislocations [53].
- In the setting of an irreconstructable radial head and neck fracture, radial head arthroplasty is an excellent option in restoring radiocapitellar contact and elbow stability [14].
- Unstable or unpredictable fixation of complex radial head fractures should probably be treated with prosthetic replacement to avoid instability of the forearm or elbow [19].
- Clinical outcome studies indicate that head replacement is a reasonable option to offer patients with comminuted radial head fractures and complex elbow trauma [2].

IMPLANT SELECTION AND DESIGN

- Bipolar-cemented implants show lower revision rates compared to other designs [13].
- Smooth stemmed implants have demonstrated lower rates of proximal radial osteolysis compared with porous ingrowth designs [53].
- There is no evidence to support one type of radial head implant design over others, with the exception of silicone prostheses that have been abandoned [53].
- Two systematic reviews concluded that there are no major differences in clinical outcomes or revision rates among radial head implant designs [53].
- A monopolar implant provides a good clinical outcome with the benefit of being cost effective compared to bipolar systems [51].

- Most commercially available implants are axisymmetric and nonanatomic, while some employ a bipolar articulation [30].

SURGICAL TECHNIQUE AND SIZING

- Adequate knowledge of the surgical indications, types of implants, and surgical technique are essential for a satisfactory outcome when a radial head prosthesis is used for the treatment of nonreconstructable radial head fractures [10].
- The diameter of the radial head arthroplasty is determined from the minor diameter of the elliptical reconstructed excised radial head, which is typically 2 mm smaller than the major diameter of the native radial head [55].
- The implant size is typically downsized one size from the native radial head to avoid overstuffing [51].
- The radial head prosthesis should articulate at the level of the radial notch, 2 mm distal to the coronoid [55].
- The proximal edge of the prosthesis should be level with the lateral coronoid edge to prevent overstuffing the radiocapitellar joint [53].
- If the radial head does not articulate well with the capitellum, downsize the stem [55].
- Translate the radial neck laterally with a Hohmann retractor to facilitate implant placement [55].
- A smooth stem prosthesis should be chosen 1 mm smaller than the maximum-sized diameter neck rasp to allow the stem to move slightly in the neck [30].
- After placing trial implants, check that the radial head articulates with the capitellum and that the proximal edge of the prosthesis sits no more than 1-mm proximal to the corner of the lesser sigmoid notch of the coronoid [51].
- Any distraction or angulation at the lateral ulnohumeral joint indicates overstuffing [51].
- A range of motion test and stability test with manual varus and valgus stress at the elbow in extension should be performed following implantation [51].
- Following insertion of the definitive radial head prosthesis, careful repair of the annular ligament and rehabilitation of any concomitant osseous and ligament injuries are required to maintain elbow stability [30].
- The annular ligament must be sectioned to adequately expose the radial head and neck and to facilitate the prosthesis insertion [30].
- Thorough irrigation is recommended to remove all bony debris to minimize the risk of heterotopic ossification [51].

COMPLICATIONS AND PITFALLS

- Anatomic radial head replacement has a risk of radiological technical mistakes that correlate to poorer outcomes [9].
- Overlengthening (overstuffing) with the placement of a radial head prosthesis that is too thick may be associated with the development of pain, stiffness, and capitellar wear [30].

- An oversized radial head implant can increase tension on the interosseous membrane with subsequent risk of stiffness and pain [53].
- More than 2 mm of lengthening can increase radiocapitellar contact pressures [53].
- Overstuffing the radial head implant can decrease the ipsilateral ulnar variance [53].
- Gapping in the lateral ulnohumeral joint line is a reliable indicator of radial head overlengthening [53].
- Changes in the medial ulnohumeral joint line were apparent only after 6 mm of overlengthening [53].
- Radial head implant maltracking causes premature capitellar cartilage wear, pain, limited rotation, and may contribute to loosening of fixed stem prostheses [30].
- Radiographic parameters are not very useful to detect overlengthening of the radial head [30].
- A radial head replacement should be close to an anatomic substitute [53].
- One mid-term to long-term concern is a lack of implant durability because of loosening of the stem with either ingrowth or cemented components [53].
- Reported in one third or more of press-fit proximal head arthroplasties, loosening causes significant proximal radial osteolysis and generally necessitates removal [53].
- Rigid implant fixation in the proximal radius has been linked to increased complications and revision rates, particularly loosening [53].
- Comparative studies between unipolar and bipolar radial head replacements have mixed results, with some suggesting higher rates of loosening in bipolar implants [53].
- Choosing the size of prosthesis by evaluating the gap between the radial head and capitellum often results in overlengthening of the radius since the lateral ligaments are often incompetent [55].
- Avoid placing Hohmann retractors anteriorly on the radial neck because of pressure on the posterior interosseous nerve [55].
- Avoid excessive thickness and diameter of the radial head [55].

OUTCOMES AND FOLLOW-UP

- Better outcomes are reported for radial head arthroplasty in terms of elbow stability, range of motion, pain, and fewer complications compared to radial head excision [7].
- The results are good to excellent in approximately 80% of patients, with a 10% to 20% reduction in strength [53].
- Pain relief is typically excellent after radial head arthroplasty [53].
- Elbow extension-flexion and pronation-supination arcs are within 10 to 20 degrees of normal values [53].
- Maintenance of ulnohumeral joint stability generally is successful [53].
- Return to a high level of function, such as sport or military duties, has a mixed and guarded prognosis [53].
- Mid-term results suggest preserved good outcomes of a smooth-stemmed modular implant at an average follow-up of over 8 years [53].
- The reproducibility of results would be improved by using a minimum follow-up of three years combined with a consensus of the definition of the reasons for failure after radial head arthroplasty [3].

- Despite significant advances in understanding complex elbow instability and implant design, radial head arthroplasty has not yet become the gold standard for treatment of non-reconstructible radial head fractures [23].
- Prosthetic replacement has uncertain long-term consequences that have yet to be elucidated [27].

MANAGEMENT OF FAILURE

Complications

- Overlengthening of the radial column is a complication of radial head replacement [1].
- A minimum follow-up of three years is required to improve the reproducibility of results for radial head arthroplasty [3].
- Midterm outcomes of EVOLVE radial head prosthesis are associated with low complication rates [6].
- Radial head arthroplasty results in fewer complications compared to radial head excision [7].
- Radial head fractures treated with open reduction and internal fixation exhibit a higher risk of complications compared to those treated with radial head arthroplasty [24].
- Radial head replacement had fewer adverse events than open reduction and internal fixation for Mason type III radial head fractures in the short-term in Chinese populations [37].
- Most removals of radial head prostheses were performed to manage elbow stiffness and heterotopic ossification rather than due to implant malfunction [38].
- Radial head arthroplasty results in modest complication rates at long-term follow-up [60].

Recovery

- Radial head arthroplasty is a reasonable option for patients with comminuted radial head fractures and complex elbow trauma [2].
- The goals of current management are aimed at restoring normal anatomical and biomechanical function, with treatment dictated by fracture type, stability, and ligamentous integrity [39].
- Open reduction and internal fixation should be pursued in the treatment of comminuted fractures of the radial head unless extenuating factors prevent the patient from participating in the postoperative rehabilitation protocol [56].
- Radial head arthroplasty provides better outcomes than radial head excision in terms of elbow stability, range of motion, pain, and fewer complications [7].
- Radial head arthroplasty has not yet become the gold standard for treatment of non-reconstructible radial head fractures [23].
- Midterm outcomes of EVOLVE radial head prosthesis are satisfactory with low associated complication rates [6].

- Reproducibility of results for radial head arthroplasty would be improved by using a minimum follow-up of three years combined with a consensus definition of the reasons for failure [3].

Key Evidence

- [L4] The review aims to shed light into overlengthening as a complication of radial head replacement and to help identify and treat it. [1] ([10.1007/s00402-020-03619-9](#))
- [L5] Clinical outcome studies of metallic radial head arthroplasty systems indicate that head replacement is a reasonable option to offer patients with comminuted radial head fractures and complex elbow trauma. [2] ([10.1016/j.jhsa.2005.12.005](#))
- [L1] The reproducibility of results would be improved by using a minimum follow-up of three years combined with a consensus of the definition of the reasons for failure after radial head arthroplasty. [3] ([10.1302/0301-620x.99b12.bjj-2017-0543.r2](#))
- [L5] The intraoperative decision to fix or replace the radial head is critical to optimize treatment outcomes. [4] ([10.1016/j.hcl.2004.06.003](#))
- [L1] Implant fixation type does not appear to affect functional outcomes of radial head arthroplasty. [5] ([10.1016/j.jse.2018.07.032](#))
- [L2] Midterm outcomes of EVOLVE radial head prosthesis are satisfactory, and associated complication rates are low. [6] ([10.1177/1758573219850111](#))
- [L4] Better outcomes are reported for radial head arthroplasty in terms of elbow stability, range of motion, pain, and fewer complications compared to radial head excision. [7] ([10.1155/2018/4020625](#))
- [L4] Due to the variety of implant designs and limited evidence, the current data provide no evidence for a specific radial head prosthesis design. [8] ([10.1302/2058-5241.4.180099](#))
- [L3] Anatomic radial head replacement has a risk of radiographic technical mistakes that correlate to poorer outcomes. [9] ([10.1016/j.jseint.2026.101671](#))
- [L5] Adequate knowledge of the surgical indications, types of implants, and surgical technique are essential for a satisfactory outcome when a radial head prosthesis is used for the treatment of nonreconstructable radial head fractures. [10] ([10.5435/jaaos-22-10-633](#))
- [L5] Most fractures of the radial head are stable and managed non-operatively with good long-term results, while displaced unstable fractures require restoration of radiocapitellar contact via reconstruction or prosthetic replacement to prevent elbow instability. [11] ([10.1302/0301-620x.95b2.29877](#))
- [L4] The preferred treatment for failed radial head arthroplasty depends mainly on the chondral condition and stability of the elbow joint. [12] ([10.1302/2058-5241.5.190055](#))
- [L4] Radial head replacement is recommended for comminuted fractures with satisfactory medium- and long-term results, though bipolar-cemented implants show lower revision rates. [13] ([10.1016/j.injury.2013.09.019](#))

- [L1] The use of stem auto-expansion as a mode of obtaining primary fixation in radial head arthroplasty appears to be an effective solution for reducing the risk of painful loosening. [15] ([10.1007/s00264-018-4070-0](#))
- [L5] The authors state that for fractures with three or more articular fragments or those not amenable to stable internal fixation, they prefer excision of the radial head and prosthetic replacement using monopolar, metallic radial head implants with modular components and a smooth neck. [18] ([10.1016/j.jhsa.2014.10.029](#))
- [L4] Unstable or unpredictable fixation of complex radial head fractures should probably be treated with prosthetic replacement to avoid instability of the forearm or elbow. [19] ([10.1016/j.jse.2010.11.011](#))
- [L5] The ligaments have the most marked influence on stability, particularly when the upper limb is positioned such that valgus and varus gravity loads are applied to the elbow. [20] ([10.1016/j.jse.2004.09.034](#))
- [L1] Recommendations for surgical treatment of radial head and neck fractures according to the Mason classification can now be given with the best available evidence. [21] ([10.1016/j.injury.2013.04.003](#))
- [L5] Despite significant advances in understanding complex elbow instability and implant design, RHA has not yet become the gold standard for treatment of non-reconstructible radial head fractures. [23] ([10.1007/s00264-018-4082-9](#))
- [L1] Mason type 3 radial head fractures treated with open reduction and internal fixation exhibit a higher risk of complications compared to those treated with radial head arthroplasty. [24] ([10.1016/j.jseint.2024.08.180](#))
- [L4] Early mobilization of the elbow is important for the restoration of elbow range of motion and function. [29] ([10.2106/jbjs.d.02710](#))
- [L1] Based on the current evidence, conservative management of isolated Mason II radial head fractures yields favorable therapeutic outcomes with a low incidence of complications. [32] ([10.1186/s13018-024-05039-6](#))
- [L5] Nondisplaced and minimally displaced radial head fractures can be treated non-operatively with early mobilization. [35] ([10.1530/eor-24-0035](#))
- [L5] Most radial head fractures can be managed nonsurgically with early motion, while complex fractures associated with elbow instability require careful selection between open reduction and internal fixation and arthroplasty. [36] ([10.5435/00124635-200707000-00003](#))
- [L1] Radial head replacement had better elbow function and fewer adverse events than ORIF for Mason type III RHF in the short-term in Chinese population, but evidences are of low quality and results may not apply in the longer term or more generally. [37] ([10.1016/j.otsr.2015.06.015](#))
- [L1] Most removals were performed to manage elbow stiffness and heterotopic ossification rather than due to implant malfunction, suggesting acceptable mid-term longevity. [38] ([10.1016/j.jhsa.2017.08.031](#))
- [L5] The goals of current management are aimed at restoring normal anatomical and biomechanical function, with treatment dictated by fracture type, stability, and ligamentous integrity. [39] ([10.1016/j.hcl.2007.01.009](#))

- [L3] Therefore, open reduction and internal fixation should be pursued in the treatment of comminuted fractures of the radial head unless extenuating factors prevent the patient from participating in the postoperative rehabilitation protocol. [56] ([10.2106/jbjs.e.00841](#))
- [L4] Our systematic review established that RHA results in satisfactory clinical outcomes and modest complication and revision rates at long-term follow-up, despite high levels of radiologic degenerative changes over the same period. [60] ([10.1016/j.jse.2021.03.142](#))

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