Journal of Hand Surgery Global Online 6 (2024) 233–235

Contents lists available at ScienceDirect

Journal of Hand Surgery Global Online

journal homepage: www.JHSGO.org

Policy Paper

Polymethyl Methacrylate for Elbow Arthroplasty: Is There Another Way?

Sumail S. Bhogal, MD, [*] Jennifer L. D'Auria, MD, [†] Sebastian V. Gehrmann, MD, [‡] Mark E. Baratz, MD, [*] Robert A. Kaufmann, MD [†]

[*] Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Pittsburgh, PA
[†] Hand and Upper Extremity Division, Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Piittsburgh, PA
[‡] Department of Orthopedic and Trauma Surgery, Katholisches Karl-Leisner Klinikum, Kleve, Germany

ARTICLE INFO

Article history:
Received for publication November 23, 2023
Accepted in revised form November 29, 2023
Available online January 1, 2024

Key words:
Biomechanics
Elbow arthroplasty
Elbow trauma
Implant science
Outcomes after arthroplasty

Polymethyl methacrylate remains the only US Food and Drug Administration-approved method of total elbow arthroplasty fixation and exhibits high aseptic loosening rates that result in challenging revision surgeries and potential morbidity secondary to bone-cement implantation syndrome. In this policy paper, the authors aim to explore the historical background of polymethyl methacrylate and the complications that arise in association with its use. We will review arthroplasty trends in the elbow and lower extremities and the challenges with the US Food and Drug Administration-approval process.

Since 1976, the only approved method for total elbow arthroplasty fixation is with the use of polymethyl methacrylate (PMMA). This material fills the void between the implant and bone and quickly dries in an exothermic reaction. How did this material become the only approved method for upper-extremity implantation? To answer this question, we must retrace our steps back to 1969 when President Richard Nixon tasked the director of the National Heart and Lung Institute, Theodore Cooper, MD, to study the regulation of medical technology. Dr Cooper's initiative recommended that the Food and Drug Administration (FDA) expand its supervision of medical devices and suggested a practical method to regulate emerging technologies.[1]

This group proposed that technology of the early 1970s be considered the state of the art. Any novel implant would be stratified by the FDA based on a perceived level of risk. Three classes were to be created. Class I devices were considered unlikely to cause injury to the patient. Class II devices were designated as posing a higher risk than class I and, therefore, required a higher level of oversight to ensure that they did not cause harm. Class II devices would also establish their safety and effectiveness by demonstrating that they were equivalent to another predicate device that was currently available on the market. Additional metrics included device performance testing, postmarket surveillance, patient registries, and labeling requirements. This procedure became known as the 510(k) pathway, named after its specific section within the 1976 Food, Drug, and Cosmetic Act. Class III devices would pose the greatest risk to the patient and would generally require a multi-million dollar premarket approval (PMA) process to establish their safety and effectiveness, which would often include clinical trials. Since its inception, the PMA process has required such substantial time and resources that only 70 orthopedic devices were cleared via the PMA pathway between 1982 and 2014.[2] The vast majority were spine implants or devices related to hip and knee arthroplasties. There were only two upper extremity implants, one each for thumb carpometacarpal arthroplasty and metacarpophalangeal implant arthroplasty.[3]

Since 1976, thousands of 510(k) applications have been received, which also have a much lower $12,745 application fee when compared with the $374,858.4 PMA fee. With this approach, change occurs in iterations, given that once a new technology is introduced via the 510(k) pathway, it then becomes the predicate for the next "substantially equivalent" design. Over the years, this process has

Declaration of interests: R.A.K. owns Arrch Orthopaedics that is developing an uncemented method of implant fixation. No benefits in any form have been received or will be received by the other author(s) related directly to this article.

Corresponding author: Robert A. Kaufmann, MD, Hand and Upper Extremity Division, Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Kaufmannn building, 3471 Fifth Avenue Pittsburgh, PA 15213.
E-mail address: kaufra@upmc.edu (R.A. Kaufmann).

https://doi.org/10.1016/j.jhsg.2023.11.006

been successful in mitigating risk with few exceptions, such as the metal-on-metal hip arthroplasty.[4,5]

In addition to categorizing risk, Dr Cooper's recommendations also established the state of the art. The technology of 1976 was grandfathered in and, because the PMA pathway is so expensive, the orthopedic industry has been reluctant to introduce novel devices or fixation methods unless the market and return on investment are large.

Problem Statement

Although PMMA is the only current FDA–approved fixation strategy for total elbow arthroplasty, it has substantial limitations and poses morbidity risks to patients.

PMMA is a synthetic polymer derived from methyl methacrylate. It is a transparent thermoplastic and is frequently referred to by one of its trade names, Plexiglas (Röhm GmbH). It was first produced in 1928, and some of the original applications were in World War II for submarine periscopes, airplane windows, turrets, and canopies. Its first application in medicine was in the 1940s to close gaps within the skull. Since 1950, bone cement has been used for anchoring prostheses and was championed in 1958 by British surgeon Sir John Charnley. Dr Charnley used cement to secure a cup into the acetabulum and a metal stem with the ball into the femur. The cement filled the free space between the implant components and bone. Barium sulfate was added to make the material radiopaque. The technique of "cementing" became the standard for fixation of total hips, knees, shoulders, wrists, and elbows. When Cooper began regulating medical devices in 1969, cement fixation of implants was so popular that it was considered "state of the art." Cement offered a quick and, in the near term, reliable bone-to-implant fixation.[6]

Unfortunately, PMMA also generates substantial heat as it dries, which is often absorbed by the implant and dissipated via blood flow through bone. Intraoperative studies have shown temperatures as high as 65°C within the cement and 56°C at the bone-cement interface. These temperatures exceed the thermal-necrosis threshold of bone (53°C).[7] Bones that are stripped of soft tissue attachments and where the cement mantle is large are vulnerable and may be damaged by this exothermic reaction. Revision efforts that use ultrasonic cement removal devices will also cause thermal damage above known thresholds for thermal necrosis.[8,9]

PMMA is designed to fill the space between the implant and bone but, in doing so, makes a cemented implant smaller than an implant otherwise would be if it did not need to share the intramedullary canal with the PMMA. By acting as a grout between the bone and the implant, it does not promote osseointegration, which is defined as "the formation of a direct interface between an implant and bone, without intervening soft tissue."[10] Without osseointegration, the bond between the PMMA and bone can weaken, leading to component instability and implant failure. An inadequate cement mantle, mechanical stress, and biological responses may all contribute to this process. One study showed 50% aseptic loosening rates at a long-term follow-up in young patients.[11]

Cementless implants employ roughened surfaces to facilitate the growth of bone into the implant. These features provide a mechanical interlock to limit micromotion before osseointegration. In the lower extremities, newly designed total knee implants are demonstrating increased durability and longevity, which may be valuable for younger and more active patient populations requiring total knee arthroplasty.[12] Currently, it is unclear whether cemented or uncemented implants are superior regarding mechanical stability.[13]

The financial cost of PMMA is not substantial even when one adds antibiotics and methylene blue dye that allows for easier identification during revision surgery. It does become more expensive when one includes the cost of an ultrasonic cement removal system and then the additional cement required with each revision effort. The real toll for the patient and surgeon lies in the difficulty in removing cement and the possibility that not all of it may be eradicated, which is unacceptable in the face of an infection. Eliminating cement is time-consuming and technically demanding because PMMA is often harder than the native bone and must be removed with chisels and curettes. Frequently, an osteotomy is performed to create bone windows that allow access to the cement. Bone fracture, cement extravasation, and injury to adjacent nerves may occur.[14,15]

Infections after total elbow arthroplasty are devastating problems. A dorsal incision through the elbow's thin soft tissue envelope and the exothermic cement curing may contribute to their incidence. To eradicate an infection, all the cement must be removed to avoid biofilm formation on the PMMA. Persistent biofilms can lead to chronic or recurrent infections, requiring additional interventions or revision surgeries and hampering the effectiveness of antibiotic treatment. To avoid infection, the use of PMMA cement with antibiotic additives (eg, gentamicin and tobramycin) is often used. Although this can help reduce the risk of infection, it may also lead to antibiotic resistance, potentially complicating future treatment options. Another troubling finding is that bacteria can survive on tobramycin-impregnated cement.[16]

Bone-cement implantation syndrome (BCIS) is a unique problem associated with cement fixation of an implant. It occurs primarily in association with cemented total hip arthroplasty and is characterized by hypoxia and hypotension occurring around the time of cementation.[17] It is poorly understood and yet remains an important cause of intraoperative mortality and morbidity. A single institution, retrospective review of all patients undergoing hip arthroplasty over 28 years, demonstrated that all 23 patients who died during surgery sustained irreversible cardiorespiratory disturbances that were initiated during cementing. No deaths were among the 15,411 uncemented hip arthroplasties.[18] In our institutional experience, one senior author (R.A.K.) had a patient develop BCIS after a cemented distal humerus hemiarthroplasty, which required prolonged extracorporeal membrane oxygenation. Although rare, the morbidity of BCIS can be devastating.

Although cementation exhibits drawbacks, the luxury of comparing implant fixation options, such as in knee or hip arthroplasty, does not exist in the realm of total elbow replacements. Current FDA regulations are needed to safeguard patients and represent a challenge to the development of novel fixation methods for total elbow arthroplasty.

Proposed Solution

One fixation consideration may be to promote osseointegration similar to what occurs in hip arthroplasty. This could be performed with an intramedullary screw incorporated into the ulnar and humeral components. As the screw advances, it would pull the implant into a cavity created by drilling and broaching efforts. A snug fit would serve to increase implant stability and allow for bone integration.[19,20]

Future Directions and Long-Term Focus

We are approaching a half-century where it has been mandatory to use bone cement for elbow arthroplasty. Given its drawbacks, alternative methods such as press fit fixation or intramedullary screw fixation may warrant consideration. In the lower extremity,

cemented and uncemented implants are being evaluated regarding implant longevity with a trend toward uncemented implants.[21,22]

Recommendations

Current FDA regulations will require a substantial approval process for any uncemented fixation option and will benefit from a concerted and collaborative effort by hand surgeons, engineers, and the FDA.

References

1. Mantus D, Pisano DJ, eds. FDA medical device regulation. In: *FDA Regulatory Affairs: Third Edition*. CRC Press; 2014:137–180.
2. Schultz HW. Federal Food, Drug, and Cosmetic Act. In: *Food Law Handbook*. Springer Netherlands; 1981:530–546.
3. Samuel AM, Rathi VK, Grauer JN, Ross JS. How do orthopaedic devices change after their initial FDA premarket approval? *Clin Orthop Relat Res*. 2016;474(4):1053–1068.
4. Shah A, Olson MM, Maurice JM. Review of approvals and recalls of US specific medical devices in general and plastic surgery. *Surg Pract Sci*. 2023;12:100158.
5. Ardaugh BM, Graves SE, Redberg RF. The 510(k) ancestry of a metal-on-metal hip implant. *N Engl J Med*. 2013;368(2):97–100.
6. Kuehn KD, Ege W, Gopp U. Acrylic bone cements: composition and properties. *Orthop Clin North Am*. 2005;36(1):17–28.
7. Berman AT, Reid JS, Yanicko DR, Sih GC, Zimmerman MR. Thermally induced bone necrosis in rabbits. Relation to implant failure in humans. *Clin Orthop Relat Res*. 1984;186:284–292.
8. Goldberg SH, Cohen MS, Young M, Bradnock B. Thermal tissue damage caused by ultrasonic cement removal from the humerus. *J Bone Joint Surg Am*. 2005;87(3):583–591.
9. Goldberg SH, Studders EM, Cohen MS. Ultrasonic cement removal in revision arthroplasty. *Orthopedics*. 2007;30(8):632–635.
10. Miller-Keane encyclopedia and dictionary of medicine, nursing, and allied health. *Gastroenterol Nurs*. 1993;15(6):258.
11. Callaghan JJ, Forest EE, Olejniczak JP, Goetz DD, Johnston RC. Charnley total hip arthroplasty in patients less than fifty years old. A twenty to twenty-five-year follow-up note. *J Bone Joint Surg Am*. 1998;80(5):704–714.
12. Prasad AK, Tan JHS, Bedair HS, Dawson-Bowling S, Hanna SA. Cemented vs. cementless fixation in primary total knee arthroplasty: a systematic review and meta-analysis. *EFORT Open Rev*. 2020;5(11):793–798.
13. Albrektsson BE, Ryd L, Carlsson LV, et al. The effect of a stem on the tibial component of knee arthroplasty. A roentgen stereophotogrammetric study of uncemented tibial components in the Freeman-Samuelson knee arthroplasty. *J Bone Joint Surg Br*. 1990;72(2):252–258.
14. Throckmorton TW, Zarkadas PC, Sanchez-Sotelo J, Morrey BF. Radial nerve palsy after humeral revision in total elbow arthroplasty. *J Shoulder Elbow Surg*. 2011;20(2):199–205.
15. Waitzenegger T, Mansat P, Guillon P, et al. Radial nerve palsy in surgical revision of total elbow arthroplasties: A study of 4 cases and anatomical study, possible aetiologies and prevention. *Orthop Traumatol Surg Res*. 2015;101(8):903–907.
16. Stoodley P, Nistico L, Johnson S, et al. Direct demonstration of viable Staphylococcus aureus biofilms in an infected total joint arthroplasty. A case report. *J Bone Joint Surg Am*. 2008;90(8):1751–1758.
17. Mudgalkar N, Ramesh KV. Bone cement implantation syndrome: a rare catastrophe. *Anesth Essays Res*. 2011;5(2):240–242.
18. Parvizi J, Holiday AD, Ereth MH, Lewallen DG. The Frank Stinchfield Award. Sudden death during primary hip arthroplasty. *Clin Orthop Relat Res*. 1999;(369):39–48.
19. Shetty S, Nelson B, Knopp B, Schneppendahl J, Kaufmann RA. Strength of humeral and ulnar intramedullary screw fixation. *J Hand Surg Am*. 2022;47(10):1014.e1–1014.e8.
20. Brånemark R, Berlin O, Hagberg K, Bergh P, Gunterberg B, Rydevik B. A novel osseointegrated percutaneous prosthetic system for the treatment of patients with transfemoral amputation: a prospective study of 51 patients. *Bone Joint J*. 2014;96-B(1):106–113.
21. Schwabe MT, Hannon CP. The evolution, current indications and outcomes of cementless total knee arthroplasty. *J Clin Med*. 2022;11(22).
22. Turkyilmaz I, Aksoy U, McGlumphy EA. Two alternative surgical techniques for enhancing primary implant stability in the posterior maxilla: a clinical study including bone density, insertion torque, and resonance frequency analysis data. *Clin Implant Dent Relat Res*. 2008;10(4):231–237.