Effects of gamma radiation as terminal sterilization on mechanical properties and organic composition of bone and skin allograft

Article Published: 02 May 2025

(2025) Cite this article

Journal of Materials Research

Aims and scope

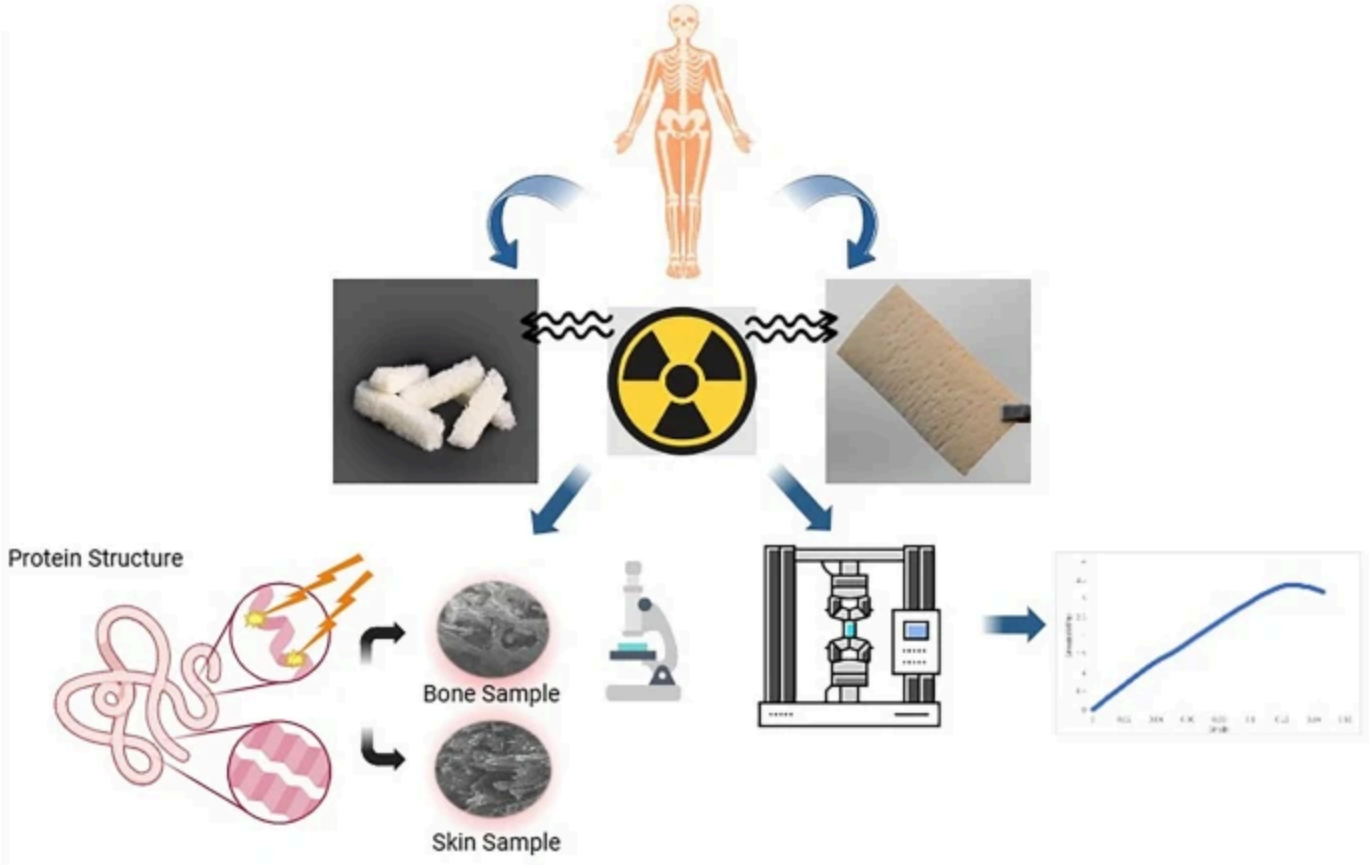
Submit manuscript

Mahsa Delyanee, Sara Tabatabaee, Reza Samanipour, Amirhossein Tavakoli ✉, Akram Alizadeh ✉ & Adel Marzban

Abstract

The increasing demand for allograft tissues in musculoskeletal repair necessitates effective sterilization methods that preserve mechanical integrity. This study investigates the effects of gamma irradiation (25 kGy) on the mechanical properties and organic composition of freeze-dried bone and skin allografts. Results showed a significant decline on average in Young's modulus (62.0 ± 0.80% for bone and 46.5 ± 0.7% for skin) and ultimate stress (23.0 ± 0.4% for bone and 31.2 ± 0.4% for skin), attributed to collagen network disruption. Hydroxyproline content decreased by 0.22–1.15 μg/mg in bone and 0.89–1.20 μg/mg in skin, confirming collagen degradation. FTIR analysis revealed alterations in amide and phosphate peaks, while SEM images indicated increased porosity and structural fragmentation. These findings highlight a critical balance between sterilization efficacy and biomechanical stability, offering insights for optimizing gamma irradiation parameters in tissue banking.

Graphical Abstract



Availability of data and material

Data supporting this study are included within the article and/or supporting materials.

Code availability

Not applicable.

References

1. R. Singh, D. Singh, A. Singh, Radiation sterilization of tissue allografts: a review. World J. Radiol. **8**(4), 355 (2016)

Article PubMed PubMed Central Google Scholar

2. S.A. Barbour, W. King, The safe and effective use of allograft tissue—an update. Am. Compr. J. Sports Med. **31**(5), 791 (2003)

Article Google Scholar

3. R. Singh, D. Singh, Gamma irradiated bone allografts processed from femoral heads. Front. Sci. **2**(5), 119 (2012)

Article Google Scholar

4. P. David, S. Singh, R. Ankar, A comprehensive overview of skin complications in diabetes and their prevention. Cureus. **15**(5), (2023)

5. S. Aldekhayel, A.M. Khubrani, K.S. Alshaalan, M. Barajaa, O. Al-Meshal, Outcomes and complications of diabetic burn injuries: a single center experience. Int. J. Burns Trauma. **11**(3), 220 (2021)

PubMed PubMed Central Google Scholar

6. K. Ou, M. Wang, C. Meng, K. Guo, N.S. Emon, J. Li, K. Qi, Y. Dai, B. Wang, Enhanced mechanical strength and stretchable ionic conductive hydrogel with double-network structure for wearable strain sensing and energy harvesting. Compos. Sci. Technol. **255**, 110732 (2024)

Article CAS Google Scholar

7. M. Megahed, S. Elkashity, A. Talaab, M. AboShaban, The impact of human skin allograft as a temporary substitute for early coverage of major burn wounds on clinical outcomes and mortality. Ann. Burns Fire Disasters **34**(1), 67 (2021)

CAS PubMed PubMed Central Google Scholar

8. A.M. Nahum, J.W. Melvin, *Accidental Injury: Biomechanics and Prevention* (Springer, Berlin, 2012)

Google Scholar

9. A. Heinz, Elastic fibers during aging and disease. Ageing Res. Rev. **66**, 101255 (2021)

Article CAS PubMed Google Scholar

10. T. Eastlund, D.M. Strong, Infectious disease transmission through tissue transplantation, in *Advances in Tissue Banking* (World Scientific, 2004), p. 51

11. H. Nguyen, D.A. Morgan, M.R. Forwood, Sterilization of allograft bone: effects of gamma irradiation on allograft biology and biomechanics. Cell Tissue Bank. **8**(2), 93 (2007)

Article PubMed Google Scholar

12. S. Zou, R.Y. Dodd, S.L. Stramer, D.M. Strong, Probability of viremia with HBV, HCV, HIV, and HTLV among tissue donors in the United States. N. Engl. J. Med. **351**(8), 751 (2004)

Article CAS PubMed Google Scholar

13. N. Rahman, R. Khan, S. Badshah, Effect of X-rays and gamma radiations on the bone mechanical properties: literature review. Cell Tissue Bank. **19**(4), 457 (2018)

Article PubMed Google Scholar

14. S.W. Shalaby, S.D. Nagatomi, E.F. Powell, 6—Sterilization techniques for biotextiles for medical applications, in *Biotextiles as Medical Implants*, ed. by M.W. King, B.S. Gupta, R. Guidoin (Woodhead

Publishing, 2013), p. 157

15. K. Brouwer, P. Geutjes, E. Versteeg, R. Wismans, J. Deprest, H. Chajra, D. Tiemessen, W. Feitz, E. Oosterwijk, W. Daamen, T. Kuppevelt, The effect of ethylene oxide sterilisation, beta irradiation and gamma irradiation on collagen fibril-based scaffolds. Evaluation of biological, physical and chemical parameters. Tissue Eng. Regen. Med. **8**, 460 (2011)

Google Scholar

16. V.L. Kudryk, M.J. Scheidt, M.J. McQuade, D.E. Sutherland, T.E. Vandyke, J.O. Hollinger, Toxic effect of ethylene-oxide-sterilized freeze-dried bone allograft on human gingival fibroblasts. J. Biomed. Mater. Res. **26**(11), 1477 (1992)

Article CAS PubMed Google Scholar

17. M. Silindir Gunay, Y. Ozer, Sterilization methods and the comparison of E-Beam sterilization with gamma radiation sterilization. FABAD J. Pharm. Sci. **34**, 43 (2009)

Google Scholar

18. A. Hoburg, S. Keshlaf, T. Schmidt, M. Smith, U. Gohs, C. Perka, A. Pruss, S. Scheffler, High-dose electron beam sterilization of soft-tissue grafts maintains significantly improved biomechanical properties

compared to standard gamma treatment. Cell Tissue Bank. **16**(2), 219 (2015)

Article CAS PubMed Google Scholar

19. A.T. Hoburg, S. Keshlaf, T. Schmidt, M. Smith, U. Gohs, C. Perka, A. Pruss, S. Scheffler, Effect of electron beam irradiation on biomechanical properties of patellar tendon allografts in anterior cruciate ligament reconstruction. Am. J. Sports Med. **38**(6), 1134 (2010)

Article PubMed Google Scholar

20. A. Dziedzic-Goclawska, A. Kaminski, I. Uhrynowska-Tyszkiewicz, W. Stachowicz, Irradiation as a safety procedure in tissue banking. Cell Tissue Bank. **6**, 201 (2005)

Article CAS PubMed Google Scholar

21. S. Girard, E. Régnier, A. Boukenter, Y. Ouerdane, J.-P. Meunier, D. Hamdani, Gamma and UV radiation-induced color centers in optical fibers, in *Materials Science Forum*, vol. 480 (Trans Tech Publ, 2005), p. 323

22. A. Dziedzic-Goclawska, A. Kaminski, I. Uhrynowska-Tyszkiewicz, W. Stachowicz, Irradiation as a safety procedure in tissue banking. Cell Tissue Bank. **6**(3), 201 (2005)

Article CAS PubMed Google Scholar

23. C.R. Harrell, V. Djonov, C. Fellabaum, V. Volarevic, Risks of using sterilization by gamma radiation: the other side of the coin. Int. J. Med. Sci. **15**(3), 274 (2018)

Article CAS PubMed PubMed Central Google Scholar

24. S. Reilly, N. Gibbs, C. Griffiths, R. Watson, M. Sherratt, Ultraviolet irradiation directly influences the structure of fibrillin microfibrils. Br. J. Dermatol. (2007)

25. N.S. El-Hansi, H.H. Said, O.S. Desouky, M.A. Khalaf, M.S. Talaat, A.M. Sallam, XRD and ATR-FTIR techniques for integrity assessment of gamma radiation sterilized cortical bone pretreated by antioxidants. Cell Tissue Bank. **22**, 305 (2021)

Article CAS PubMed Google Scholar

26. O. Akkus, R.M. Belaney, P. Das, Free radical scavenging alleviates the biomechanical impairment of gamma radiation sterilized bone tissue. J. Orthop. Res. **23**(4), 838 (2005)

Article PubMed Google Scholar

27. Y. Wan, D. Liu, X. Wang, L. Wang, R. Ma, Z. Jiang, W. Li, B. Gao, J. Zhang, Y. Hu, Temperature-based protection of biochemical and biomechanical characteristics during 25 kGy 60Co irradiation for allograft tendons (2024)

28. D.B. Crocker, T.M. Hering, O. Akkus, M.E. Oest, C.M. Rimnac, Dose-dependent effects of gamma radiation sterilization on the collagen matrix of human cortical bone allograft and its influence on fatigue crack propagation resistance. Cell Tissue Bank. **25**(3), 735 (2024)

Article CAS PubMed PubMed Central Google Scholar

29. B. Burton, A. Gaspar, D. Josey, J. Tupy, M.D. Grynpas, T.L. Willett, Bone embrittlement and collagen modifications due to high-dose gamma-irradiation sterilization. Bone **61**, 71 (2014)

Article CAS PubMed Google Scholar

30. A. Kaminski, A. Jastrzebska, E. Grazka, J. Marowska, G. Gut, A. Wojciechowski, I. Uhrynowska-Tyszkiewicz, Effect of gamma irradiation on mechanical properties of human cortical bone: influence of different processing methods. Cell Tissue Bank. **13**(3), 363 (2012)

Article CAS PubMed Google Scholar

31. C. Gaidau, M. Râpă, G. Ionita, I.R. Stanculescu, T. Zaharescu, R.-R. Constantinescu, A. Lazea-Stoyanova, M. Stanca, The influence of gamma radiation on different gelatin nanofibers and gelatins. Gels **10**(4), 226 (2024)

Article CAS PubMed PubMed Central Google Scholar

32. A. Mansor, A.F. Ariffin, N. Yusof, S. Mohd, S. Ramalingam, A.P. Md Saad, R. Baharin, N.W. Min, Effects of processing and gamma radiation on mechanical properties and organic composition of frozen, freeze-dried and demineralised human cortical bone allograft. Cell Tissue Bank. **24**(1), 25 (2023)

Article CAS PubMed Google Scholar

33. H. Mrazova, J. Koller, G. Fujerikova, P. Babal, Structural changes of skin and amnion grafts for transplantation purposes following different doses of irradiation. Cell Tissue Bank. **15**(3), 429 (2014)

Article CAS PubMed Google Scholar

34. S. Khosla, Pathogenesis of age-related bone loss in humans. J. Gerontol. Ser. A Biomed. Sci. Med. Sci. **68**(10), 1226 (2013)

Article CAS Google Scholar

35. R.M. Zebaze, A. Ghasem-Zadeh, A. Bohte, S. Iuliano-Burns, M. Mirams, R.I. Price, E.J. Mackie, E. Seeman, Intracortical remodelling and porosity in the distal radius and post-mortem femurs of women: a cross-sectional study. Lancet **375**(9727), 1729 (2010)

Article PubMed Google Scholar

36. J.N. Farr, S. Khosla, Skeletal changes through the lifespan—from growth to senescence. Nat. Rev. Endocrinol. **11**(9), 513 (2015)

Article PubMed PubMed Central Google Scholar

37. D.B. Crocker, T.M. Hering, O. Akkus, M.E. Oest, C.M. Rimnac, Dose-dependent effects of gamma radiation sterilization on the collagen matrix of human cortical bone allograft and its influence on fatigue crack propagation resistance. Cell Tissue Bank. **1** (2024)

38. A. Eckersley, M. Ozols, R. O'Cualain, E.-J. Keevill, A. Foster, S. Pilkington, D. Knight, C.E. Griffiths, R.E. Watson, M.J. Sherratt, Proteomic fingerprints of damage in extracellular matrix assemblies. Matrix Biol. Plus **5**, 100027 (2020)

Article PubMed PubMed Central Google Scholar

39. S.A. Hibbert, R.E. Watson, C.E. Griffiths, N.K. Gibbs, M.J. Sherratt, Selective proteolysis by matrix metalloproteinases of photo-oxidised dermal extracellular matrix proteins. Cell. Signal. **54**, 191 (2019)

Article CAS PubMed Google Scholar

40. S. Reilly, N. Gibbs, C. Griffiths, R. Watson, M. Sherratt, Ultraviolet irradiation directly influences the structure of fibrillin microfibrils (2007)

41. M. Wei, X. He, N. Liu, H. Deng, Role of reactive oxygen species in ultraviolet-induced photodamage of the skin. Cell Div. **19**(1), 1 (2024)

Article CAS PubMed PubMed Central Google Scholar

42. N. Yoganandan, A.M. Nahum, J.W. Melvin, *Accidental Injury: Biomechanics and Prevention* (Springer, Berlin, 2014)

Google Scholar

43. A.A. Poundarik, P.-C. Wu, Z. Evis, G.E. Sroga, A. Ural, M. Rubin, D. Vashishth, A direct role of collagen glycation in bone fracture. J. Mech. Behav. Biomed. Mater. **52**, 120 (2015)

Article CAS PubMed PubMed Central Google Scholar

44. E. Morgan, M. Bouxsein, Biomechanics of bone and age-related fractures. Princ. Bone Biol. Two-Vol. Set. **1**, 29 (2008)

45. S. Ganguly, D. Ray, P. Das, P.P. Maity, S. Mondal, V. Aswal, S. Dhara, N.C. Das, Mechanically robust dual responsive water dispersible-graphene based conductive elastomeric hydrogel for tunable pulsatile drug release. Ultrason. Sonochem. **42**, 212 (2018)

Article CAS PubMed Google Scholar

46. A. Hamer, J. Strachan, M. Black, C. Ibbotson, I. Stockley, R. Elson, Biomechanical properties of cortical allograft bone using a new method of bone strength measurement: a comparison of fresh, fresh-frozen and irradiated bone. J. Bone Jt. Surg Br. Vol. **78**(3), 363 (1996)

Article CAS Google Scholar

47. A. Kaminski, A. Jastrzebska, E. Grazka, J. Marowska, G. Gut, A. Wojciechowski, I. Uhrynowska-Tyszkiewicz, Effect of gamma irradiation on mechanical properties of human cortical bone: influence of different processing methods. Cell Tissue Bank. **13**, 363 (2012)

Article CAS PubMed Google Scholar

48. O. Cornu, X. Banse, P.L. Docquier, S. Luyckx, C. Delloye, Effect of freeze-drying and gamma irradiation on the mechanical properties of human cancellous bone. J. Orthop. Res. **18**(3), 426 (2000)

Article CAS PubMed Google Scholar

49. D.B. Burr, Changes in bone matrix properties with aging. Bone **120**, 85 (2019)

Article CAS PubMed Google Scholar

50. Y. Bala, E. Seeman, Bone's material constituents and their contribution to bone strength in health, disease, and treatment. Calcif. Tissue Int. **97**, 308 (2015)

Article CAS PubMed Google Scholar

51. E.A. Zimmermann, E. Schaible, H. Bale, H.D. Barth, S.Y. Tang, P. Reichert, B. Busse, T. Alliston, J.W. Ager III., R.O. Ritchie, Age-related changes in the plasticity and toughness of human cortical bone at multiple length scales. Proc. Natl. Acad. Sci. **108**(35), 14416 (2011)

Article CAS PubMed PubMed Central Google Scholar

52. J. Kamml, C.-Y. Ke, C. Acevedo, D.S. Kammer, The influence of AGEs and enzymatic cross-links on the mechanical properties of collagen fibrils. J. Mech. Behav. Biomed. Mater. **143**, 1058 (2023)

Article Google Scholar

53. S. Park, Biochemical, structural and physical changes in aging human skin, and their relationship. Biogerontology **23**(3), 275 (2022)

Article CAS PubMed PubMed Central Google Scholar

54. I. Komara, A. Susanto, A. Amaliya, B. Abbas, Y. Warastuti, I. Hendiani, A. Miranda, A.P. Erliani, The effect of gamma-ray irradiation on the physical, mechanical, and morphological characteristics of PVA-collagen-chitosan as a guided tissue regeneration (GTR) membrane material. Eur. J. Dent. **17**(02), 530 (2023)

Article PubMed Google Scholar

55. G.J. Fisher, B. Wang, Y. Cui, M. Shi, Y. Zhao, T. Quan, J.J. Voorhees, Skin aging from the perspective of dermal fibroblasts: The interplay between the adaptation to the extracellular matrix microenvironment and cell autonomous processes. J. Cell Commun. Signal. **17**(3), 523 (2023)

Article CAS PubMed PubMed Central Google Scholar

56. B. Thomas, D. McIntosh, T. Fildes, L. Smith, F. Hargrave, M. Islam, T. Thompson, R. Layfield, D. Scott, B. Shaw, Second-harmonic generation imaging of collagen in ancient bone. Bone Rep. **7**, 137 (2017)

Article CAS PubMed PubMed Central Google Scholar

57. D. de Cassan, A.L. Hoheisel, B. Glasmacher, H. Menzel, Impact of sterilization by electron beam, gamma radiation and X-rays on electrospun poly-(ε-caprolactone) fiber mats. J. Mater. Sci. Mater. Med. **30**, 1 (2019)

Article Google Scholar

58. M. Stanca, C. Gaidau, T. Zaharescu, G.-A. Balan, I. Matei, A. Precupas, A.R. Leonties, G. Ionita, Physico-chemical changes induced by Gamma irradiation on some structural protein extracts. Biomolecules **13**(5), 774 (2023)

Article CAS PubMed PubMed Central Google Scholar

59. A.H. Gage, A.P. MacKenzie, D. Baker, H.E. Newman, Considerations in determination of residual moisture in lyophilized demineralized bone matrix: the role of residual moisture analyzers. Cell Tissue Bank. **14**(2), 243 (2013)

Article CAS PubMed Google Scholar

60. R.E. Neuman, M.A. Logan, The determination of hydroxyproline. J. Biol. Chem. **184**(1), 299 (1950)

Article CAS PubMed Google Scholar

Acknowledgments

We sincerely thank Forensic Medicine Center of Tehran for their valuable cooperation in preparing the raw material and basic information needed to write this article.

Funding

This research was financially supported by Iranian Tissue Product (ITP) Company.

Author information

Authors and Affiliations

Research and Development Department, Iranian Tissue Product Company, Tehran, Iran
Mahsa Delyanee, Sara Tabatabaee, Reza Samanipour & Adel Marzban

Iranian Tissue Bank and Research Center, Tehran University of Medical Sciences, Tehran, Iran
Amirhossein Tavakoli

Nervous System Stem Cells Research Center, Semnan University of Medical Sciences, Semnan, Iran
Akram Alizadeh

Contributions

M.D., A.M., and S.T. carried out the experiment. M.D. and S.T. wrote the manuscript with support from R.S. A.T. and A.A. helped in supervising the project. M.D. conceived the original idea.

Corresponding authors

Correspondence to Amirhossein Tavakoli or Akram Alizadeh.

Ethics declarations

Conflict of interest

The authors report there are no competing interests to declare.

Ethical approval

All human rights were concerned in this research. All the tissues (as the raw material) were utilized after obtaining the written consent of the next of kin. Also, this project was approved by research ethics committee of Semnan University of Medical Sciences and Health Services with the approval ID of IR.SEMUMS.REC.1403.110.

Consent to participate

Not applicable.

Consent for publication

The verbal consent of the next of kin was obtained for the data publication provided that the donor's name would not be disclosed.

Additional information

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Rights and permissions

About this article

Cite this article

Delyanee, M., Tabatabaee, S., Samanipour, R. *et al.* Effects of gamma radiation as terminal sterilization on mechanical properties and organic composition of bone and skin allograft. *J. Mater. Res.* (2025). https://doi.org/10.1557/s43578-025-01584-w

Received
22 October 2024

Accepted
18 April 2025

Published
02 May 2025

DOI
https://doi.org/10.1557/s43578-025-01584-w