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HISTORICAL MEDICAL MATERIALS IN MUSEUM COLLECTIONS: TECHNOLOGICAL DEVELOPMENT, DEGRADATION AND CONSERVATION OF METALS, GLASS, WAX AND EARLY POLYMERS

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Abstract

Historical medical collections preserve material evidence of technological development, clinical practice, anatomical education, and institutional use. This critical review examines four representative material groups—metals and alloys, medical and pharmaceutical glass, wax-based anatomical models, and rubber and early synthetic polymers—with emphasis on their degradation mechanisms, analytical investigation, and conservation requirements. Recent literature published between 2020 and 2026 was evaluated to identify material-specific vulnerabilities and transferable conservation approaches. Metals are primarily affected by corrosion, embrittlement, and surface alteration; historical glass by ion exchange, leaching, crizzling, and environmental instability; wax models by deformation, cracking, and composite-material interactions; and early polymers by molecular degradation, plasticizer migration, discoloration, shrinkage, and volatile emissions. Non-destructive and minimally invasive techniques, including X-ray-based imaging, XRF, Raman spectroscopy, FT-IR, SEM-EDS, and diffraction methods, are central to material identification and condition assessment. The review supports a risk-based conservation strategy integrating material composition, deterioration activity, environmental sensitivity, evidence of use, and object complexity. Preventive conservation and prioritized monitoring should generally precede invasive treatment in heterogeneous medical heritage collections.

Keywords: *Medical heritage; Conservation science; Historical materials; Degradation; Analytical characterization; Preventive conservation*

Introduction

Historical medical collections constitute a distinctive category of material heritage in which scientific practice, technological innovation, craftsmanship, and institutional history converge. Medical objects are not merely obsolete instruments or teaching aids; their materials, manufacturing traces, modifications, and patterns of use preserve evidence of changing approaches to diagnosis, treatment, anatomical education, and laboratory practice [1], [2], [3]. Among the most representative objects are anatomical teaching models, whose composite construction and material complexity illustrate the close relationship between medical knowledge

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and material technology. Recent studies on historical wax collections have demonstrated the importance of documenting original fabrication techniques while integrating digital recording, three-dimensional reconstruction, and minimally invasive conservation strategies [4], [5], [6].

The investigation of historical medical objects increasingly relies on non-destructive and three-dimensional imaging approaches capable of revealing internal morphology and structural relationships without compromising object integrity [7]. Metals and alloys represent a particularly important component of medical heritage because of their extensive historical use in surgical, diagnostic, mechanical, and laboratory equipment. Their preservation is complicated by alloy composition, manufacturing processes, surface treatments, environmental exposure, and previous interventions. Studies of copper, silver, bronze, iron, and lead heritage materials have shown that embrittlement, stratified corrosion, surface contamination, and chemically active corrosion products may substantially alter both structural stability and historical appearance [8], [9], [10]. Environmental conditions and burial or exposure histories further influence corrosion behavior, while inappropriate cleaning may remove technologically or historically significant surface information [11], [12], [13].

Glass constitutes another major material class in pharmaceutical, laboratory, diagnostic, and therapeutic collections. Although traditionally perceived as chemically durable, historical glass may undergo ion exchange, surface hydration, leaching, crizzling, cracking, and progressive loss of transparency. Its preservation therefore depends strongly on environmental monitoring, appropriate cleaning strategies, and systematic condition assessment [14]-[18].

The twentieth century introduced increasingly diverse polymeric materials into medical objects. Cellulose nitrate, cellulose acetate, plasticized polyvinyl chloride, and other early synthetic polymers are particularly problematic because degradation may involve molecular breakdown, plasticizer migration, discoloration, embrittlement, and volatile emissions [19], [20], [21]. Their reliable identification frequently requires chromatographic and spectroscopic techniques, including FT-IR-based approaches capable of characterizing chemically altered historical polymers [22], [23], [24]. Advanced analytical methods, including synchrotron-based X-ray diffraction, further expand the possibilities for material identification and degradation assessment in complex heritage objects [25]. Accordingly, this review examines metals, glass, wax, and early polymers through an integrated framework linking technological development, degradation mechanisms, analytical investigation, and conservation decision-making.

Review Methodology

This critical review was designed to synthesize recent evidence concerning the technological characteristics, deterioration mechanisms, analytical investigation, and conservation of historical medical materials. The literature search focused on publications issued between 2020 and 2026 and was conducted using PubMed, Scopus, Web of Science, and Google Scholar. The search strategy combined terms related to historical medical objects and museum collections with material- and conservation-specific keywords, including “historical medical instruments,” “medical museum collections,” “heritage metals corrosion,” “historical medical glass,” “wax anatomical models conservation,” “cellulose nitrate conservation,” “cellulose acetate degradation,” “historical polymers,” “XRF cultural heritage,” “Raman spectroscopy conservation,” and “non-destructive imaging heritage.”

The review focused on four material groups that are particularly relevant to historical medical collections: metals and alloys, medical and pharmaceutical glass, wax-based anatomical models, and rubber and early synthetic polymers. Studies were considered eligible when they addressed at least one of the following aspects: historical material use, manufacturing technology, material composition, degradation processes, condition assessment, analytical characterization, preventive conservation, or conservation treatment. Priority was given to peer-reviewed studies directly related to cultural heritage, museum collections, historical scientific objects, or materials presenting degradation mechanisms transferable to historical medical collections.

Publications concerned exclusively with contemporary clinical performance, modern implant materials, drug-delivery systems, tissue engineering, or current biomedical applications were excluded from the core evidence base. Methodological studies outside the immediate field of medical heritage were retained only when the analytical approaches described were directly applicable to the non-destructive or minimally invasive characterization of historical objects, particularly three-dimensional imaging, surface characterization, elemental analysis, molecular spectroscopy, and structural assessment [25]-[30].

The selected literature was organized according to material category and comparatively examined across four principal dimensions: material composition and technological characteristics, mechanisms and indicators of deterioration, analytical methods suitable for identification and condition assessment, and implications for conservation practice. Particular attention was given to non-destructive and minimally invasive approaches, including X-ray fluorescence, Raman spectroscopy, FT-IR, X-ray-based imaging, and complementary microscopic or diffraction techniques [25], [28], [30]. Evidence concerning environmental control, material instability, preventive conservation, and collection-level risk assessment was also incorporated [27], [31].

Rather than applying a purely descriptive synthesis, the reviewed evidence was compared across material classes to identify recurrent conservation problems, material-specific vulnerabilities, and transferable analytical strategies. This comparative approach provided the basis for the proposed material-oriented conservation framework linking composition, deterioration activity, analytical uncertainty, environmental sensitivity, evidence of historical use, and treatment priority.

Historical Development of Medical Materials

The evolution of medical materials reflects the progressive interaction between clinical needs, technological capabilities, and the availability of materials with suitable mechanical, chemical, optical, and modeling properties. Historical medical collections, therefore, preserve not only instruments and teaching objects but also evidence of successive technological transitions in medical practice and education [1], [2], [3]. Anatomical models represent a particularly illustrative example. Wax became an important material for anatomical teaching because it could reproduce complex morphology, color, and surface detail with a degree of realism that supported both medical instruction and public demonstration [3]-[6]. The surviving collections also reveal increasingly sophisticated fabrication methods, composite constructions, pigments, internal supports, and later repair interventions, all of which influence present-day conservation requirements [4], [5], [6].

Metals and alloys developed in parallel as essential materials for instruments requiring strength, hardness, dimensional stability, and repeated mechanical use. Copper alloys, iron-based materials, silver-containing alloys, bronze, and later increasingly standardized metallic compositions were employed in functional objects whose manufacturing and surface-finishing techniques left identifiable technological signatures [8], [9]. Their long-term preservation is closely linked to alloy composition, manufacturing history, environmental exposure, and the formation of corrosion layers, which may range from relatively stable patinas to structurally damaging or chemically active products [8]-[13].

Glass became indispensable in pharmaceutical, laboratory, diagnostic, and therapeutic contexts because transparency permitted visual inspection of contents, while its chemical resistance and formability supported the manufacture of containers and precision objects. Historical glass, however, is not uniformly stable; variations in composition and prolonged environmental exposure can promote ion exchange, surface hydration, leaching, crizzling, and progressive structural deterioration [14]-[18].

The expansion of industrial chemistry during the nineteenth and twentieth centuries introduced rubber, cellulose derivatives, plasticized polymers, and other synthetic materials into medical and technical objects. These materials offered flexibility, lightness, moldability, insulation, and opportunities for serial production, but many early formulations are intrinsically unstable [19]-[24]. Their deterioration may involve chain degradation, plasticizer loss or migration, discoloration, shrinkage, embrittlement, and surface alteration, making visual identification alone unreliable [19]-[24]. Consequently, historical medical collections increasingly require material-specific analytical strategies that integrate technological interpretation with modern conservation science.

Taken together, these successive material transitions show that the historical function of medical objects cannot be separated from the physical and chemical properties of the materials from which they were made. The principal material groups considered in this review differ substantially in their original medical functions, representative object types, characteristic deterioration pathways, and present conservation requirements. These relationships are summarized in Table 1, which provides a comparative overview of the four material classes examined in the following sections.

Table 1. Selected historical medical materials, representative applications, degradation patterns, and principal conservation concerns

Material group	Historical medical applications	Representative objects	Principal degradation patterns	Main conservation concerns
Metals and alloys	Cutting, gripping, probing, measurement, mechanical support, and sterilization-related functions.	Scalpels, forceps, scissors, needles, probes, trays, and diagnostic or laboratory instruments.	Uniform, pitting, crevice, and galvanic corrosion; embrittlement; loss of plated layers; surface contamination.	Differentiate active corrosion from stable patina; preserve maker's marks, wear, and repair traces; avoid excessive polishing; and apply humidity control and selective stabilization [8]-[13].
Medical and pharmaceutical glass	Containment, observation, measurement, storage, and administration of liquids.	Bottles, ampoules, syringes, thermometers, laboratory vessels, and optical components.	Ion exchange, surface leaching, haze, crizzling, cracking, flaking, and interactions with residues or closures.	Identify chemically unstable glass; monitor environmental conditions; use cautious cleaning; preserve labels, closures, and historically relevant residues [14]-[18].
Wax-based anatomical models	Anatomical teaching, pathological demonstration, dermatology, obstetrics, and medical education.	Anatomical moulages, sectional models, pathological models, and teaching specimens.	Creep, deformation, cracking, surface bloom, pigment alteration, dust adhesion, and failure of internal supports.	Maintain stable temperature and low light; limit vibration and handling; support deformed structures; and preserve composite components and associated labels [3]-[6].
Rubber and early synthetic polymers	Flexible, insulating, sealing, moulded, prosthetic, and therapeutic applications.	Tubing, masks, stoppers, gloves, prosthetic elements, housings, and accessories.	Oxidation, hardening, embrittlement, plasticizer migration, shrinkage, discoloration, exudation, and volatile emissions.	Confirm polymer identity; isolate actively degrading objects; use compatible storage materials and ventilation where required; favor preventive conservation [19]-[24].

Material-Specific Conservation Challenges

Historical medical objects present markedly different conservation requirements depending on their material composition, manufacturing technology, degree of use, and environmental history. Metals, glass, wax, and early polymers differ substantially in their physical behavior and degradation pathways; consequently, conservation strategies must be adapted to the specific vulnerabilities of each material class rather than applied uniformly across collections.

Metals and Alloys

Metals and alloys are widespread in historical medical collections because their mechanical strength, durability, and machinability made them suitable for surgical instruments, diagnostic devices, laboratory equipment, and structural components. Their present condition is strongly influenced by alloy composition, manufacturing processes, previous surface treatments, and exposure to moisture, salts, pollutants, or incompatible materials [8]-[13].

Copper- and silver-based alloys may undergo long-term microstructural and chemical changes that contribute to embrittlement and loss of mechanical integrity [8]. Bronze objects frequently develop stratified corrosion layers whose morphology and composition provide information on both material history and deterioration processes; SEM-EDS and optical microscopy are particularly useful for distinguishing metallic substrates from corrosion products and deposited contaminants [9]. Iron-based heritage materials may develop complex corrosion systems that coexist with old coatings or surface residues, making cleaning and stabilization technically challenging [10]. Environmental factors, including soil chemistry and exposure conditions, can further modify corrosion kinetics and the composition of alteration layers [11], [13].

Conservation interventions must therefore distinguish between active corrosion and stable historical surface alteration. Aggressive polishing or indiscriminate corrosion removal may eliminate manufacturing traces, patina, or evidence of use. Current approaches favor detailed characterization, controlled removal of unstable products, and minimally invasive treatment strategies, including targeted cleaning methods where appropriate [10], [12].

Medical and Pharmaceutical Glass

Historical glass is commonly represented by pharmaceutical bottles, laboratory vessels, ampoules, syringes, measuring devices, and other objects requiring transparency and chemical containment. Despite its apparent durability, glass stability varies significantly according to composition, manufacturing technology, environmental exposure, and interaction with stored residues or associated materials [14]-[18].

Chemical instability often begins at the glass surface through ion exchange and selective leaching. Accumulation of soluble species may progressively alter the surface and contribute to haze, loss of transparency, microcracking, or crizzling [14], [15]. Environmental humidity is particularly important, because unstable glasses may undergo repeated hydration and dehydration cycles that accelerate surface deterioration [15]-[18]. Condition surveys have consequently emphasized the need for systematic identification of unstable objects and long-term monitoring at the collection level [16], [17], [18].

Cleaning requires particular caution. Experimental evidence indicates that contact with water may influence degradation processes differently depending on glass composition and condition, meaning that aqueous cleaning cannot be considered universally safe [17]. Prior to intervention, assessment should include visual documentation, identification of surface instability, and evaluation of deposits, labels, closures, or historically significant residues. Preventive conservation based on controlled environmental conditions and appropriate storage remains central to the long-term preservation of vulnerable glass collections [16], [17], [18].

Wax-Based Anatomical Models

Wax anatomical models are among the most complex objects in medical heritage because they combine scientific representation with highly sensitive organic materials and, frequently, composite internal structures. Their historical importance derives from their role in anatomical teaching and the realistic reproduction of human morphology, color, and pathological detail [3]-[6].

Wax formulations may contain natural waxes, resins, pigments, fillers, and other additives, while models can incorporate textiles, hair, glass elements, wooden bases, metal supports, or labels. This heterogeneity produces multiple pathways of deterioration. Temperature fluctuations may induce softening, creep, deformation, or structural displacement, whereas low temperatures and aging may increase brittleness and cracking. Surface contamination, pigment alteration, previous repairs, and deformation of internal supports may further compromise object stability [4], [5], [6].

Conservation should therefore prioritize environmental stability, minimal handling, physical support, and accurate documentation before intervention. Digital technologies have become particularly valuable because they permit non-contact recording, three-dimensional reconstruction, replication of missing volumes, and design of customized supports without extensive manipulation of the original object [4], [5]. Recent studies of historical anatomical collections also demonstrate that conservation must preserve not only the wax surface but also the technological and pedagogical information embedded in fabrication methods, assembly systems, and associated documentation [3], [6].

Rubber and Early Synthetic Polymers

Rubber and early synthetic polymers introduced new functional properties into medical objects, including flexibility, insulation, transparency, reduced weight, and compatibility with mass production. However, many early polymer formulations are intrinsically unstable and may deteriorate even under apparently acceptable museum conditions [19]-[24].

Cellulose nitrate and cellulose acetate undergo progressive chemical degradation that can be monitored through changes in molecular composition and spectroscopic response [19], [22]. Plasticized PVC is particularly sensitive to plasticizer migration and interactions with surrounding packaging or storage materials, making enclosure selection an important conservation factor [20]. Other historical plastics may exhibit discoloration, surface exudation, shrinkage, cracking, embrittlement, or loss of transparency, and these visible changes may result from complex interactions between polymer matrices, pigments, additives, and environmental conditions [21], [24].

Because visually similar objects may be manufactured from chemically different polymers, visual examination alone is insufficient for reliable identification. FT-IR spectroscopy has become particularly important for distinguishing polymer types and detecting chemical alteration, while chromatographic methods can provide additional information on molecular degradation and formulation [19], [22], [23]. Non-invasive reflection FT-IR techniques further expand analytical possibilities where sampling must be avoided [23].

For deteriorating polymers, preventive conservation is often more appropriate than extensive treatment. Appropriate isolation, inert supports, controlled light exposure, compatible wrapping materials, and avoidance of conditions that promote volatile accumulation or plasticizer migration are essential measures [19], [20], [24]. Material identification should therefore precede intervention, because conservation requirements differ substantially among cellulose derivatives, PVC, rubber, and other early synthetic polymers. The principal degradation pathways affecting the four material groups are comparatively summarized in Figure 1, highlighting their distinct physical and chemical vulnerabilities.

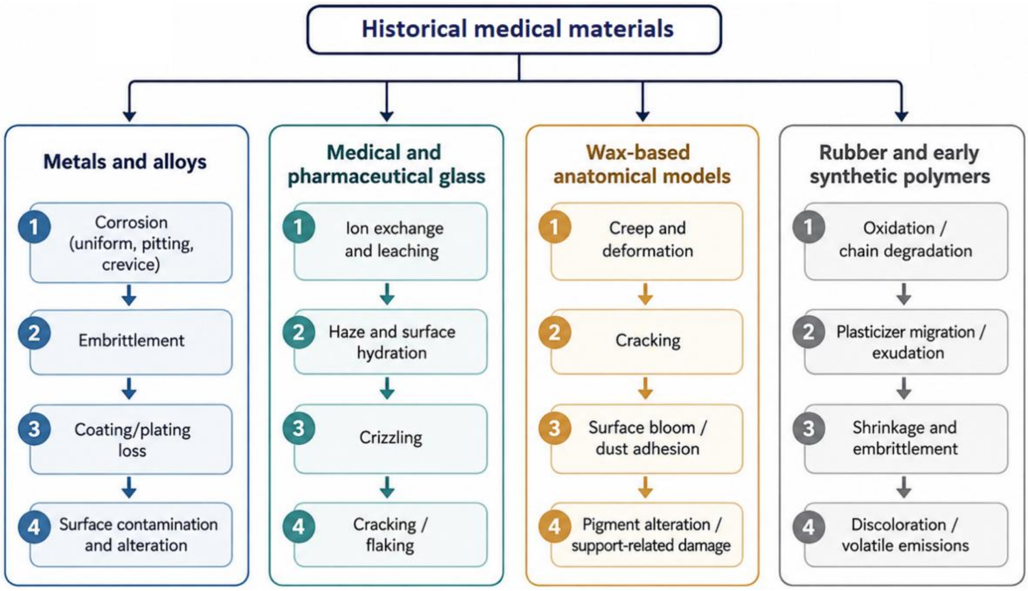

Fig. 1. Comparative degradation pathways of metals, glass, wax-based anatomical models, and early synthetic polymers in historical medical collections

Evidence of Use, Analytical Investigation and Conservation Decision-Making

Historical medical objects should be interpreted not only through their constituent materials but also through the physical and chemical evidence accumulated during manufacture, clinical use, sterilization, repair, storage, and previous conservation. These factors may alter surfaces and internal structures in ways that are difficult to distinguish from active deterioration. Consequently, analytical investigation should precede intervention whenever cleaning, stabilization, or restoration could remove historically significant information.

Use, Sterilization, Repair and Contamination

Wear patterns, scratches, sharpening traces, deformation, repaired joints, replacement components, and surface deposits may document the functional history of medical objects and should not automatically be classified as damage. In metallic objects, corrosion morphology and stratification can reflect both environmental exposure and previous surface treatments, while invasive cleaning may remove technologically relevant corrosion layers or historical residues [9]-[13]. Glass objects may retain pharmaceutical residues, deposits, labels, closures, or other associated materials whose removal can compromise historical interpretation; moreover, unstable glass surfaces may respond unpredictably to aqueous cleaning [14]-[17].

Wax anatomical models frequently contain later repairs, added supports, surface reintegrations, or structural interventions that form part of their conservation history [4], [5], [6]. Similarly, early polymers may interact chemically with wrapping materials, pigments, additives, and neighboring objects, resulting in migration products, discoloration, or surface exudation that require careful distinction from external contamination [19]-[24]. Documentation of such alterations is therefore essential before treatment.

Comparative Analytical Workflow

A stepwise analytical strategy is preferable to the indiscriminate application of multiple techniques. Initial assessment should include high-resolution photography, dimensional recording, condition mapping, examination of inscriptions and manufacturing marks, and documentation of previous repairs. Three-dimensional imaging can provide additional structural information in complex objects while limiting physical intervention [7], [29].

Subsequent analytical methods should be selected according to the conservation question. X-ray fluorescence provides rapid, non-destructive elemental characterization and is particularly useful for metals, pigments, fillers, and selected glass compositions [28]. SEM-EDS can provide localized compositional information and characterize corrosion layers or heterogeneous surfaces when access or sampling conditions permit [9], [26]. Raman spectroscopy offers non-destructive molecular identification of pigments, corrosion products, and other heritage materials [30], whereas FT-IR methods are particularly valuable for waxes, polymers, coatings, and organic degradation products [19], [23], [24]. Advanced X-ray diffraction, including synchrotron-based approaches, can resolve crystalline phases and complex alteration products where conventional methods provide insufficient information [25]. The analytical sequence should therefore progress from documentation and non-contact examination toward increasingly specialized techniques only when additional information is expected to influence conservation decisions. The principal analytical techniques applicable to the four material groups, together with the conservation questions they address, are summarized in Table 2.

Table 2. Analytical techniques by material group and principal conservation question

Material group	Preferred techniques	Main conservation question
Metals and alloys	XRF; SEM-EDS, and XRD [9], [25, [28]	Alloy identification; corrosion products; coatings and surface alteration [8]-[13]
Medical and pharmaceutical glass	XRF; SEM-EDS; Raman/FT-IR [14], [17], [28], [30]	Bulk/surface composition; leaching; residues and coatings [14]-[18]
Wax-based anatomical models	FT-IR; Raman; X-radiography/3D imaging [4], [5], [6], [30]	Wax/resin identification; pigments; internal supports and deformation [3]-[6]
Rubber and early synthetic polymers	ATR-FTIR; Raman; chromatography [19], [22], [23], [24], [30]	Polymer identification; additives; molecular degradation and migration [19]-[24]

Conservation Priority Framework

Conservation prioritisation should integrate material instability, evidence of active deterioration, object complexity, historical significance of surface alterations, and potential risks to neighboring objects or collections. Preventive-conservation studies demonstrate that environmental requirements should be adapted to the actual material response of objects rather than imposed uniformly across heterogeneous collections [27]. Collection-level risk assessment similarly provides a structured basis for identifying objects requiring immediate intervention, improved environmental control, analytical investigation, or continued monitoring [31].

Accordingly, objects showing active corrosion, progressive cracking, deformation, polymer exudation, or chemically unstable emissions should receive the highest priority. A second category should include objects whose condition cannot be adequately interpreted without further analytical characterization. Stable but environmentally sensitive objects should be managed primarily through preventive measures, while materially robust objects may remain under routine monitoring. This framework emphasizes that conservation decisions should result from the combined interpretation of material composition, deterioration activity, historical evidence, analytical findings, and environmental vulnerability rather than from visual appearance alone [27], [31]. The proposed conservation decision pathway is summarized in Figure 2, integrating material instability, active deterioration, historical sensitivity, analytical uncertainty, and collection-level risk.

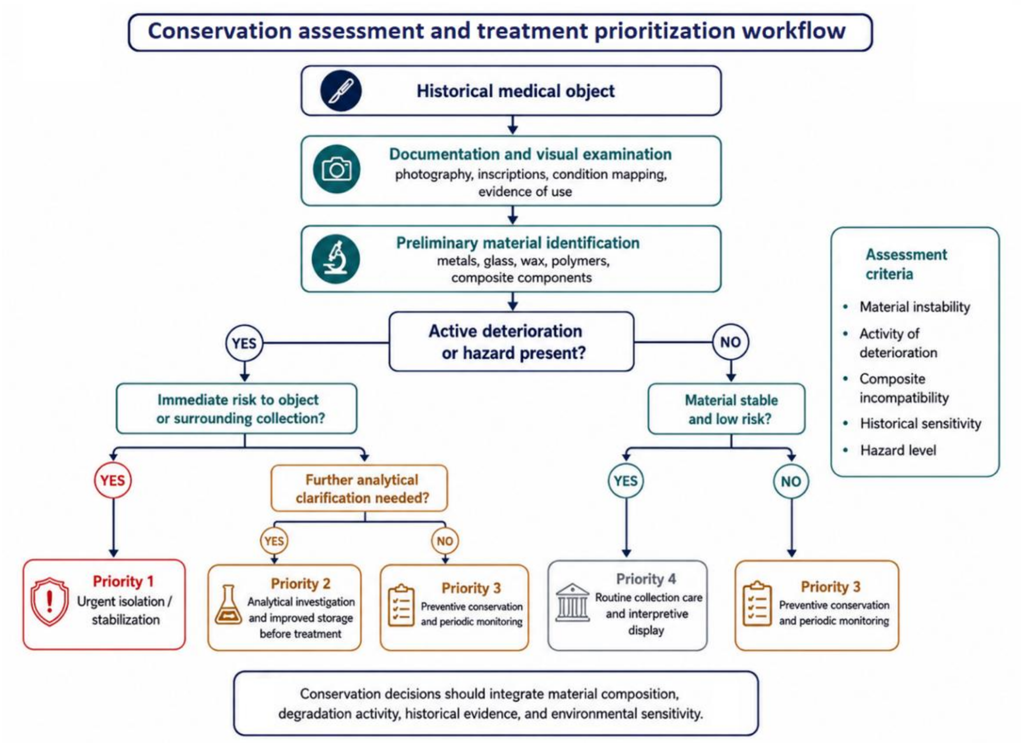

Fig. 2. Proposed decision workflow for conservation assessment and treatment prioritization of historical medical objects

Discussion

The comparative assessment of metals, glass, wax-based anatomical models, and early synthetic polymers highlights that historical medical collections should be approached as heterogeneous material systems rather than as uniform categories of technical objects. Although these materials were originally selected because they provided specific functional advantages—mechanical strength, transparency, anatomical realism, flexibility, or chemical resistance—the same properties that supported their historical use now determine markedly different patterns of deterioration. Consequently, conservation decisions cannot be based solely on object type or visual appearance. They require simultaneous consideration of material composition, manufacturing technology, evidence of use, environmental exposure, and the activity of ongoing degradation. This interpretation is consistent with material-oriented preventive conservation models, in which environmental requirements and treatment priorities are adapted to the actual response of individual objects rather than imposed uniformly across collections [27], [31].

Metallic medical objects illustrate particularly well the distinction between visible alteration and active deterioration. Corrosion products may constitute either unstable reaction layers requiring intervention or historically meaningful surfaces recording manufacture, use, cleaning, sterilization, or previous storage conditions [8]-[13]. Recent studies of scientific and technical museum collections have further demonstrated that corrosion risk is strongly influenced by relative humidity, pollutants, exhibition materials, enclosure design, and interactions with adjacent organic components [32]. This finding is especially relevant to medical instruments, which are frequently preserved together with wooden cases, textile linings, rubber elements, paper labels, or polymeric components. Conservation treatments must therefore remain selective. Comparative work on lacquered brass shows that cleaning effectiveness varies substantially according to corrosion morphology and the chemistry of the applied complexing agents, reinforcing the need to characterize surfaces before treatment [33]. Similarly, experimental studies on bronze demonstrate that corrosion layers formed under different environments may exhibit different protective or destabilizing behaviors [34]. Protective approaches based on organic coatings or phosphonic acid systems may provide effective corrosion control, but their suitability depends on the state of the patina, substrate composition, and long-term compatibility with the object [35], [36]. The influence of alloy chemistry itself should also not be underestimated, as early corrosion processes in copper- and silver-based materials vary according to elemental composition and environmental exposure [37]. These observations support a conservative strategy in which analytical characterization precedes mechanical or chemical cleaning and in which preservation of stable historical surfaces is preferred whenever active deterioration is absent.

The same principle applies to protective layers on metals. Non-invasive optical and electromagnetic techniques can provide useful information on the presence, thickness, distribution, and condition of polymeric coatings without requiring sampling [38]. For historical medical instruments, such methods are particularly valuable because polished, plated, lacquered, or coated surfaces may represent original technological features rather than later interventions. Their removal may therefore erase evidence of manufacturing practice or institutional maintenance. This strengthens the argument that conservation assessment should distinguish original surface finishes, functional wear, historical repair, and active degradation before any cleaning strategy is selected.

Historical glass presents a contrasting conservation problem because severe chemical instability may develop while the object remains apparently intact. Ion exchange, hydration, alkali depletion, and progressive network alteration can precede visible haze, crizzling, cracking, or flaking [14]-[18]. Experimental studies on silicate glass exposed to aggressive environments confirm that deterioration depends strongly on composition, surface condition, and protective treatments [39]. Micro-FTIR investigation of weathered glass has further shown that alteration products can be chemically differentiated even where macroscopic examination provides limited information [40]. These findings support the inclusion of molecular characterization within condition assessment, especially when historical pharmaceutical or diagnostic glass retains residues, labels, coatings, or closures. Non-contact imaging methods can complement compositional analysis: reflectance transformation imaging under different illumination conditions improves the visualization of micro-features and surface alteration that might otherwise remain undetected [41]. Long-term conservation experience with unstable "weeping" glass also demonstrates that appropriate humidity management can substantially influence deterioration behavior [42]. Moreover, macro-XRF studies of vitreous heritage materials show that instrumental analysis can resolve compositional and taxonomic uncertainties that cannot be addressed reliably through visual classification alone [43]. For medical glass collections, these observations favor systematic monitoring, cautious cleaning, and analytical confirmation of instability rather than intervention based only on transparency or apparent surface cleanliness.

Wax-based anatomical models require an even more integrated interpretation because their significance derives simultaneously from material composition, craftsmanship, medical pedagogy, and visual representation. Earlier studies have shown that conservation must account for composite construction, pigments, internal armatures, previous repairs, and associated display systems [3]-[6]. Recent applications of three-dimensional technologies to dermatological teaching models demonstrate that digital documentation and replica production can preserve morphological information while reducing manipulation of fragile originals [44]. Computed tomography and morphable digital modeling similarly provide access to internal structures, concealed supports, and deformation patterns that cannot be assessed externally [45]. More generally, X-CT reconstruction has emerged as a valuable tool for monitoring structural change and supporting conservation planning without dismantling or sampling complex heritage objects

[46]. These methods are particularly appropriate for wax anatomical models because intervention based solely on surface appearance may overlook deformation of internal supports, detachment between layers, or structural stress within the composite system. Digital recording should therefore be regarded not merely as a documentation technique but as part of a preventive strategy that can reduce handling and guide customized support design.

Early synthetic polymers present perhaps the greatest challenge to collection-level conservation because degradation can be chemically active, difficult to reverse, and capable of affecting neighboring objects. Visual identification is unreliable, particularly for cellulose nitrate, cellulose acetate, plasticized PVC, and other early formulations that may exhibit similar color or surface appearance despite markedly different aging pathways [19]-[24]. Non-invasive FT-IR approaches using external reflection or transflection provide important advantages where direct contact or sampling is undesirable [47]. Chemometric analysis of cellulose nitrate has demonstrated that spectroscopic changes can be used to characterize progressive degradation [48], while digital image analysis based on RGB parameters offers an additional means of mapping yellowing and monitoring spatially heterogeneous deterioration [49]. Studies of composite objects containing cellulose-nitrate coatings further show that conservation treatments applied to one component may influence the degradation behavior of another, emphasizing the risks associated with incompatible materials and previous interventions [50]. Equally important, investigations of museum storage environments demonstrate that degrading plastics may contribute to indoor pollutants while simultaneously responding to airborne contaminants, creating reciprocal interactions between objects and their surroundings [51]. These findings strongly support isolation, ventilation where appropriate, compatible storage materials, and periodic analytical monitoring rather than aggressive restoration of unstable polymers.

Taken together, the evidence across the four material groups indicates that composite construction is one of the most important determinants of conservation complexity. A medical object may combine metal, glass, wax, rubber, paper, textile, wood, adhesives, coatings, or residual pharmaceutical substances, each with different environmental sensitivities and degradation products. Deterioration of one component can accelerate damage in another through moisture retention, volatile emissions, corrosion-promoting ions, mechanical stress, or migration of additives. For this reason, storage requirements should be determined by the most vulnerable or chemically active component rather than by the visually dominant material. Analytical methods should likewise be selected according to a defined conservation question. XRF and SEM-EDS are particularly informative for elemental composition and corrosion layers [9], [28]; Raman spectroscopy can identify pigments and crystalline alteration products [30]; FT-IR is especially effective for waxes and polymers [19], [23], [24], and advanced X-ray techniques can reveal internal structures and crystalline phases while minimizing physical intervention [25].

The proposed conservation priority framework, therefore, reflects a broader shift from object-centered restoration toward evidence-based collection management. Objects exhibiting active corrosion, progressive glass instability, structural deformation, polymer exudation, or hazardous emissions require higher priority than visually damaged but chemically stable objects. Conversely, historical wear, sterilization traces, repairs, residues, and stable patinas should not automatically be removed because they may constitute documentary evidence of clinical practice and technological history. The principal contribution of this review is therefore not the identification of a single preferred treatment but the integration of material identification, degradation activity, environmental sensitivity, historical evidence, analytical uncertainty, and composite-object interactions into a unified decision process. Such an approach is particularly appropriate for medical heritage collections, where scientific, technological, pedagogical, and clinical significance are inseparable from the physical materials through which they have been preserved.

Conclusions

Historical medical objects represent complex material records in which technological development, clinical function, manufacturing practice, and subsequent use are inseparably linked. Metals and alloys, medical glass, wax-based anatomical models, and early synthetic polymers illustrate markedly different degradation pathways, ranging from corrosion and chemical instability to deformation, molecular breakdown, and additive migration. Their conservation therefore requires material-specific assessment rather than standardized intervention.

Across all four material groups, accurate characterization is fundamental for distinguishing active deterioration from stable historical alteration and for selecting appropriate conservation measures. Non-destructive and minimally invasive approaches, including X-ray-based imaging, XRF, Raman spectroscopy, FT-IR, and complementary microscopic or diffraction techniques, are particularly valuable because they can provide compositional and structural information while preserving object integrity. Evidence of use, sterilization, repair, contamination, and previous conservation should also be documented before cleaning or restoration, as these features may contribute substantially to the historical significance of the object.

The most appropriate conservation strategy is therefore an integrated, risk-based approach combining material identification, deterioration activity, environmental sensitivity, object complexity, and historical value. Preventive conservation, targeted analytical investigation, and prioritized monitoring should precede invasive treatment whenever possible, particularly for unstable glass, composite wax models, corroding metals, and degrading polymers. Such an approach supports more consistent decision-making at the collection level while preserving both the physical integrity and documentary value of historical medical heritage.

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