investigate potential differences in long-term peri-implant bone remodeling between the two membrane types.

2. MATERIALS AND METHODS

2.1 Sample Size Considerations

The sample size for this retrospective study was determined based on case availability, with a total of 53 patients, 29 patients in the collagen membrane group and 24 patients in the pericardium membrane group. A power analysis was conducted for descriptive and exploratory purposes to evaluate the long-term outcomes of Class II and III alveolar bone defects treated with two types of resorbable membranes (collagen and pericardial). The primary outcome, marginal bone loss at 5 years, was treated as a continuous variable. Comparisons between groups were planned using a two-sided independent samples t-test, with a significance level of $\alpha = 0.05$. Given the available sample size of 29 patients in the collagen membrane group and 24 patients in the pericardium membrane group, the study has an estimated statistical power of approximately 70% to detect a large effect size (Cohen's $d \approx 0.9$), corresponding to differences considered clinically relevant. Analyses focused not only on statistical significance but also on estimation of effect sizes and 95% confidence intervals.

2.2 Outcome measures

Participants were included in the study according to the following criteria:

- Adult patients (≥18 years) treated with dental implants associated with resorbable membranes (native collagen or pericardium) for Class II or III bone defects.

- Availability of good-quality radiographs at baseline and 5 years.

- Complete follow-up of at least 5 years post-surgery.

- Absence of severe systemic diseases that could compromise bone healing (e.g., untreated severe osteoporosis, active autoimmune diseases).

Conversely, the following exclusion criteria were applied:

- Patients with previous bone regeneration procedures at the same site.

- Presence of active infections or uncontrolled periodontal disease at the time of surgery.

- Patients undergoing pharmacological therapies that may interfere with bone healing (e.g., bisphosphonates, recent maxillofacial radiotherapy).

- Non-compliant patients or those without a complete 5-year follow-up.

Outcomes of this retrospective investigations were divided into primary and secondary.

Primary outcome:

- Marginal Bone Loss (MBL) at 5 years, measured on radiographs immediately after implant placement and at 5 years of follow-up.

Secondary outcome:

- Implant failures

- Qualitative assessment of peri-implant soft tissue inflammation using a gingival inflammation index

2.3 Surgery protocols

Patients were allocated into two groups according to the membrane employed.

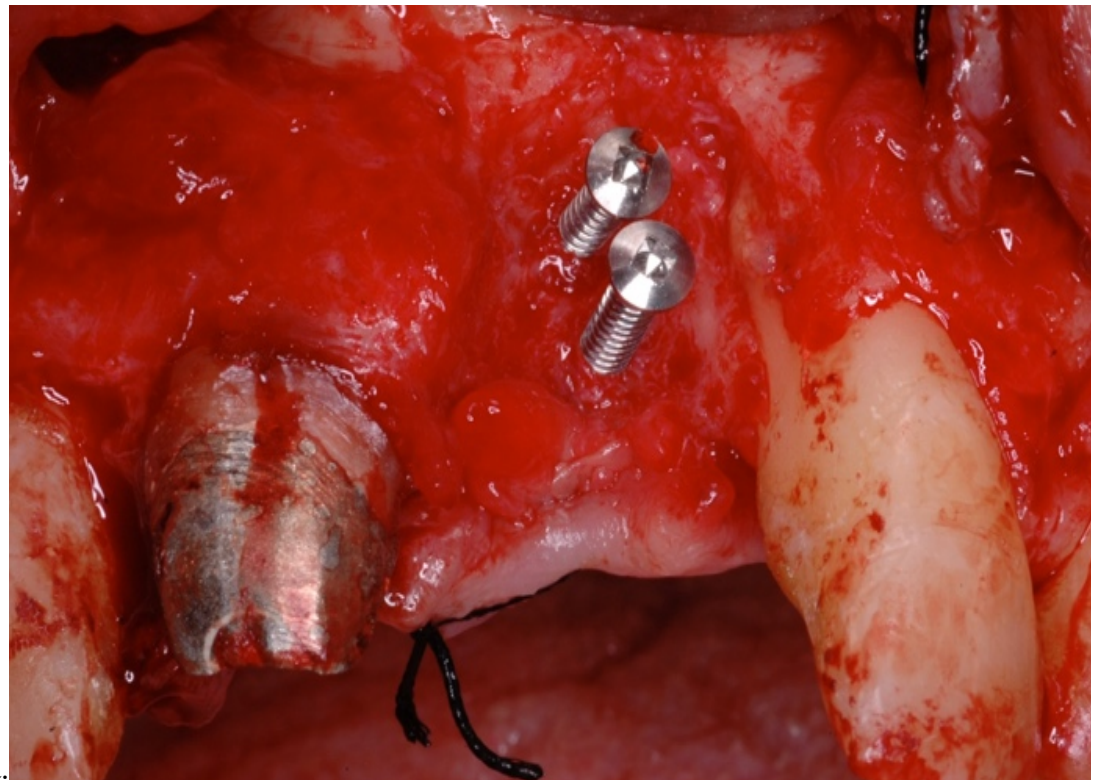
- Group A: native collagen membrane
  Deproteinized bovine bone mineral mixed with 50% autologous bone was used as graft material and covered with a resorbable collagen membrane stabilized by tenting screws, when needed.
- Group B: pericardium membrane
  Deproteinized bovine bone mineral mixed with 50% autologous bone was covered with a collagen pericardium membrane stabilized by tenting screws, when needed.

All surgical procedures were performed following standardized protocols. In both groups, flap elevation, graft placement, barrier stabilization, and tension-free wound closure were carried out according to established GBR principles.
Reviewer-oriented clarification: the use of the same grafting material in both groups was intended to isolate the effect of the barrier system on regenerative outcomes.

Surgical procedure – Group A, B

For group A, following preoperative clinical examination and three-dimensional radiographic assessment of the recipient site, standard disinfection protocols and local anesthesia were applied. A crestal incision was performed, and a full-thickness mucoperiosteal flap was elevated to fully expose the defect area. Vertical releasing incisions were avoided whenever possible and were performed only when necessary to prevent flap tearing and to allow for tension-free closure.
The recipient site was carefully debrided to remove fibrous tissue and non-vital bone using hand curettes under copious saline irrigation. Autologous bone was subsequently harvested from the mandibular ramus using a bone scraper and temporarily stored in sterile saline solution. The harvested autologous bone was then mixed in a 1:1 ratio with a deproteinized bovine bone mineral to obtain the final grafting material.

a.



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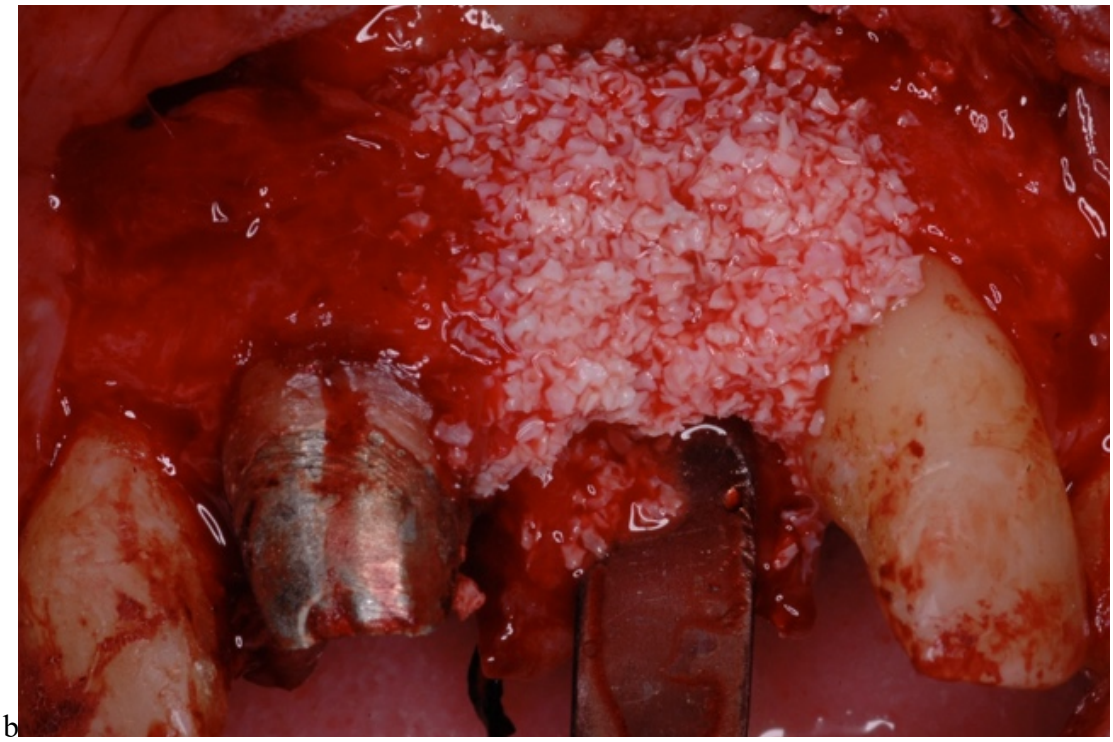

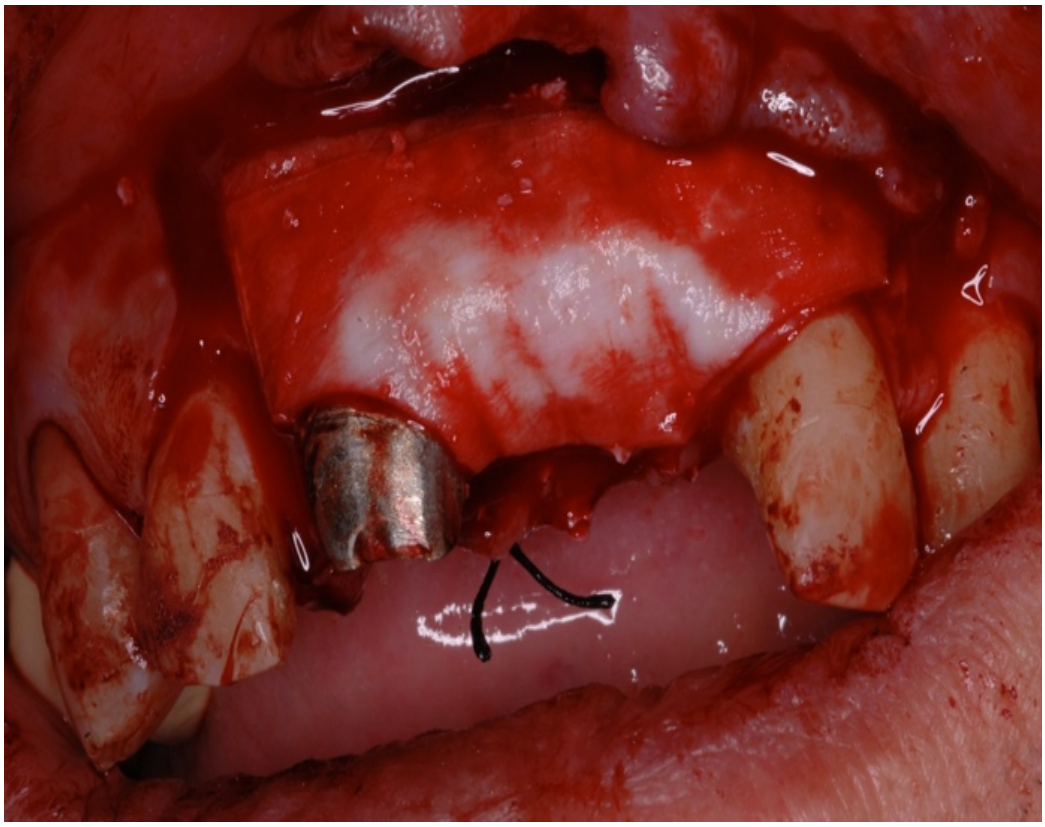

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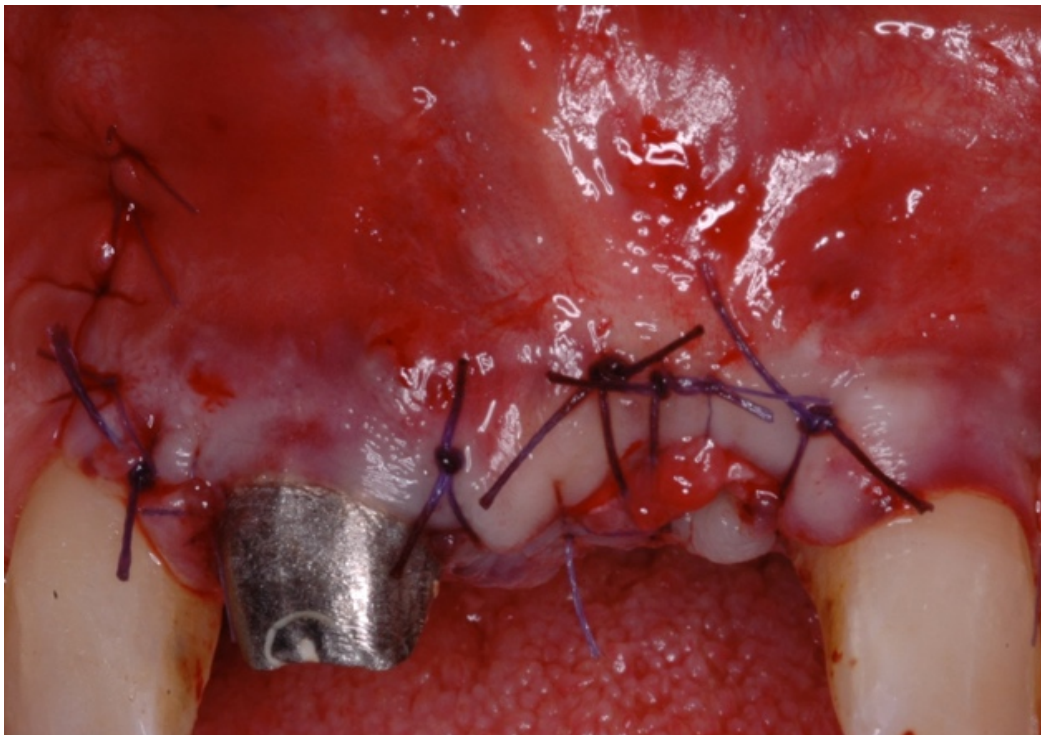


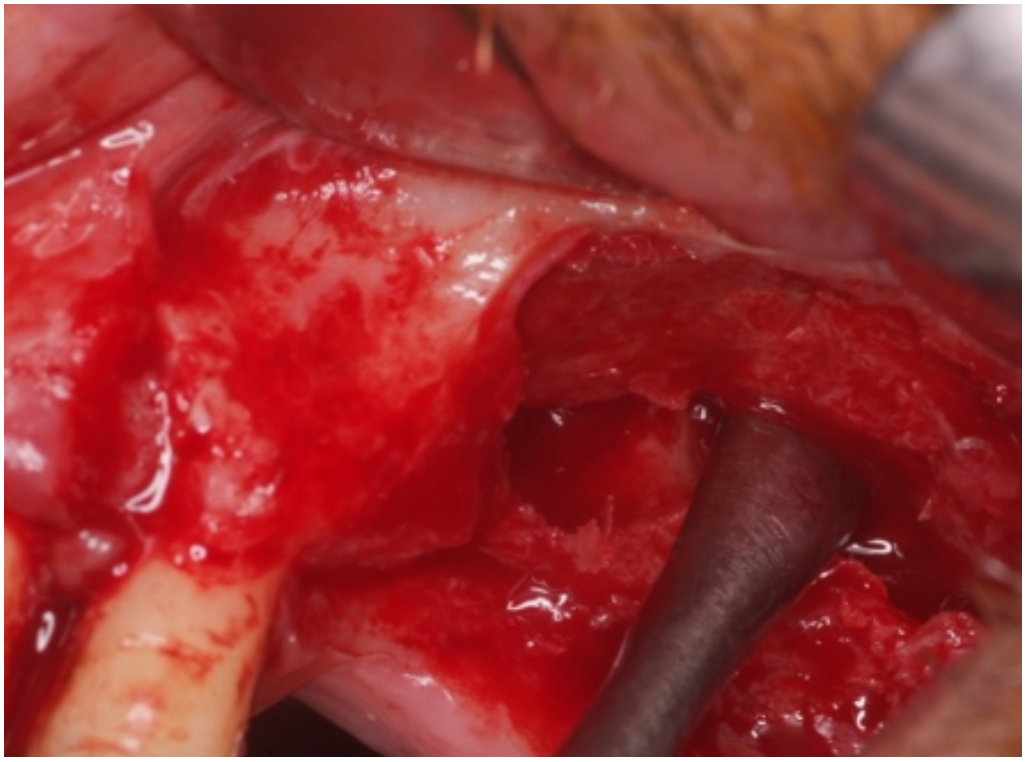
d.

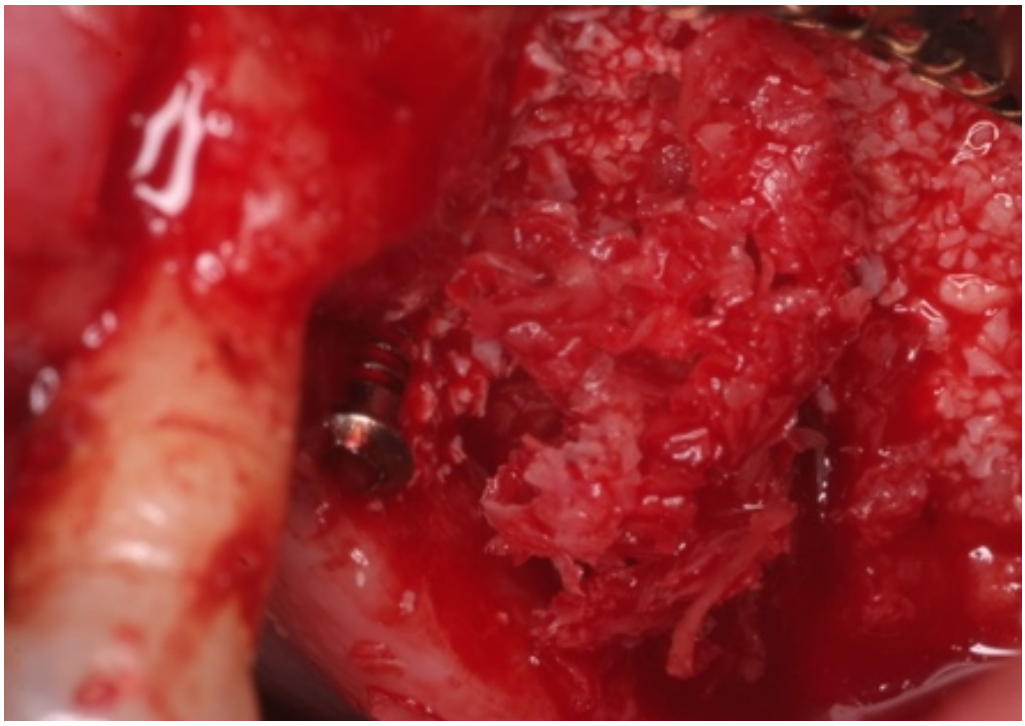
Case of Tent-pole Group (A) a) defect debrided and tenting screws in place b) mixture of autogenous bone and xenograft c) double layer collagen membrane d) suture.

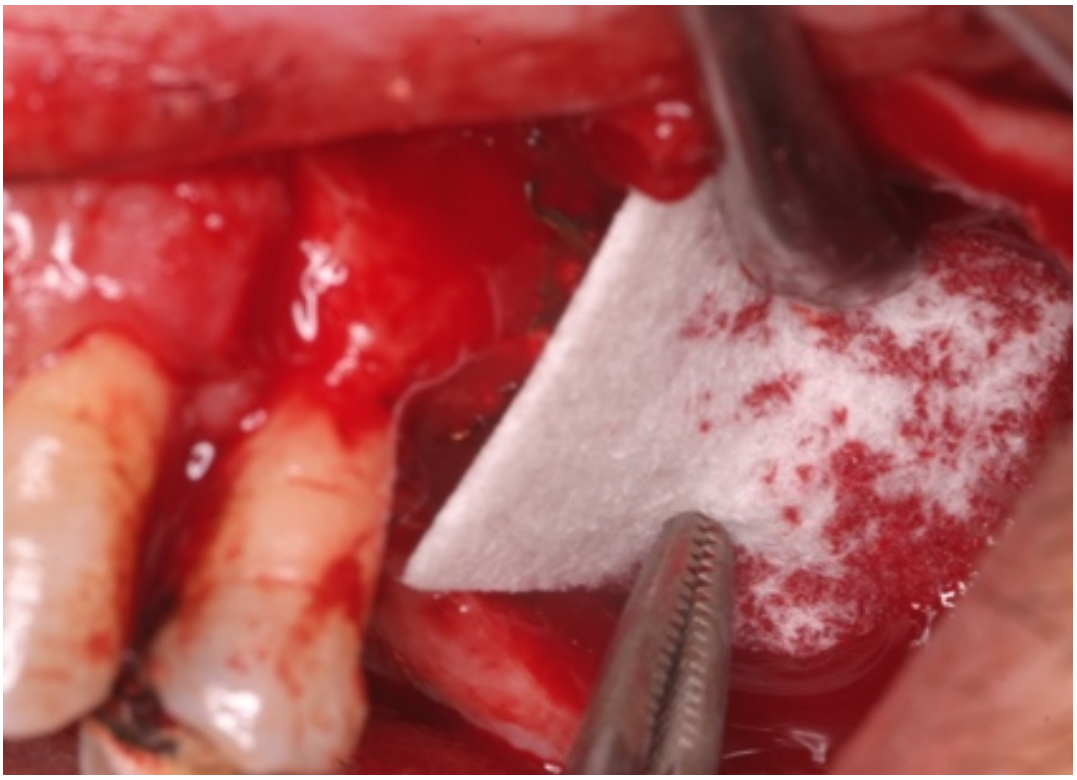
Titanium tenting screws were placed, when needed, to maintain the regenerative space and prevent membrane collapse without exerting excessive pressure on the underlying tissues. The graft material was then gently packed into the defect, ensuring complete defect filling and contouring while avoiding excessive compression.
A resorbable native collagen membrane was subsequently positioned to cover the grafted area. The membrane was carefully adapted to ensure complete coverage of the defect and stabilized with fixation pins, avoiding tension or displacement. Primary wound closure was achieved through passive flap advancement, facilitated by periosteal releasing incisions. Suturing was performed using a double-layer technique, consisting of internal horizontal mattress sutures at the mucogingival junction and superficial interrupted sutures.

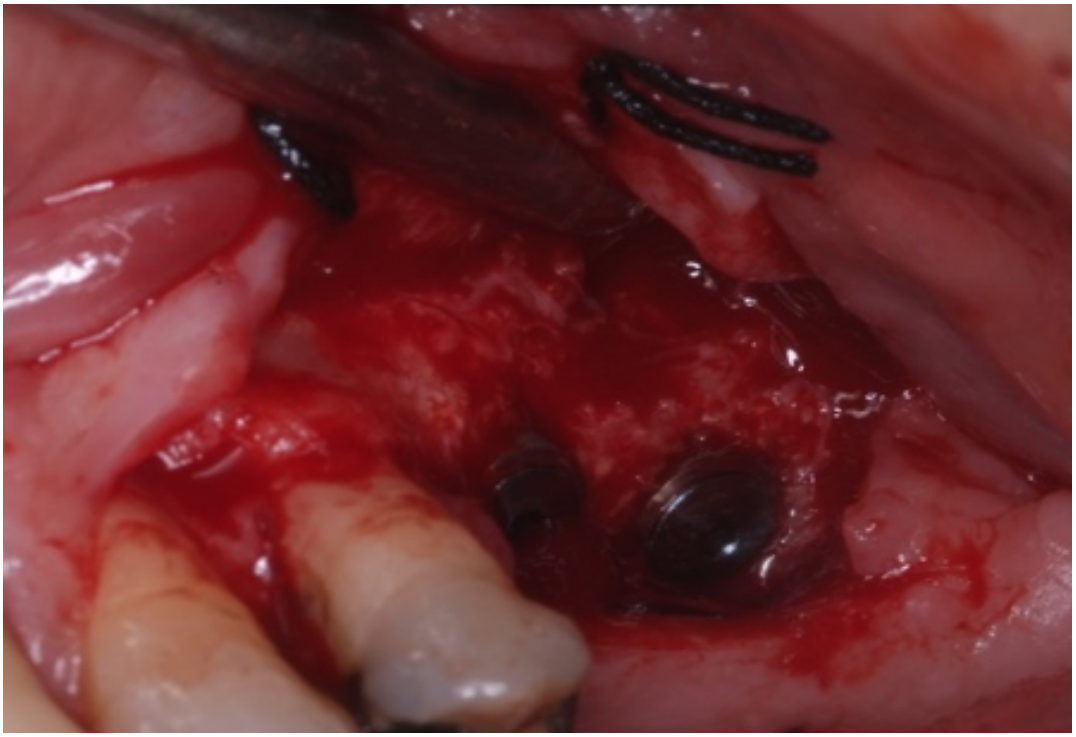
Postoperative follow-up included clinical evaluations at 7 and 14 days after surgery. Radiographic assessment using three-dimensional imaging was performed at 6 months postoperatively for all patients.
A standardized postoperative pharmacological regimen was prescribed for both groups. Antibiotic prophylaxis consisted of amoxicillin–clavulanic acid (1 g every 8 h) initiated one day prior to surgery and continued for a total of 6 days. Patients with a documented penicillin allergy received azithromycin (500 mg once daily), starting the day before surgery. Given the extent of flap elevation and bone exposure, systemic corticosteroids (betamethasone) were administered postoperatively (2 mg daily for the first 2 days, followed by 1 mg daily for the subsequent 3 days). Analgesic medication was prescribed on an as-needed basis.
Plaque control was maintained using chlorhexidine mouth rinses (0.2%) four times daily for 14 days. Patients were instructed to avoid mechanical cleaning of the surgical site during the initial healing phase.

For Group B the surgical steps were similar to those used for Group A, with the only difference was related to the use of a collagen pericardium membrane.

a. 

b. 

c. 

d. 

A case of maxillary vertical bone augmentation a) b) and c) ; d) shows the 7 months follow up and the implant placement in the regenerated area.

2.4 Radiographic measurements

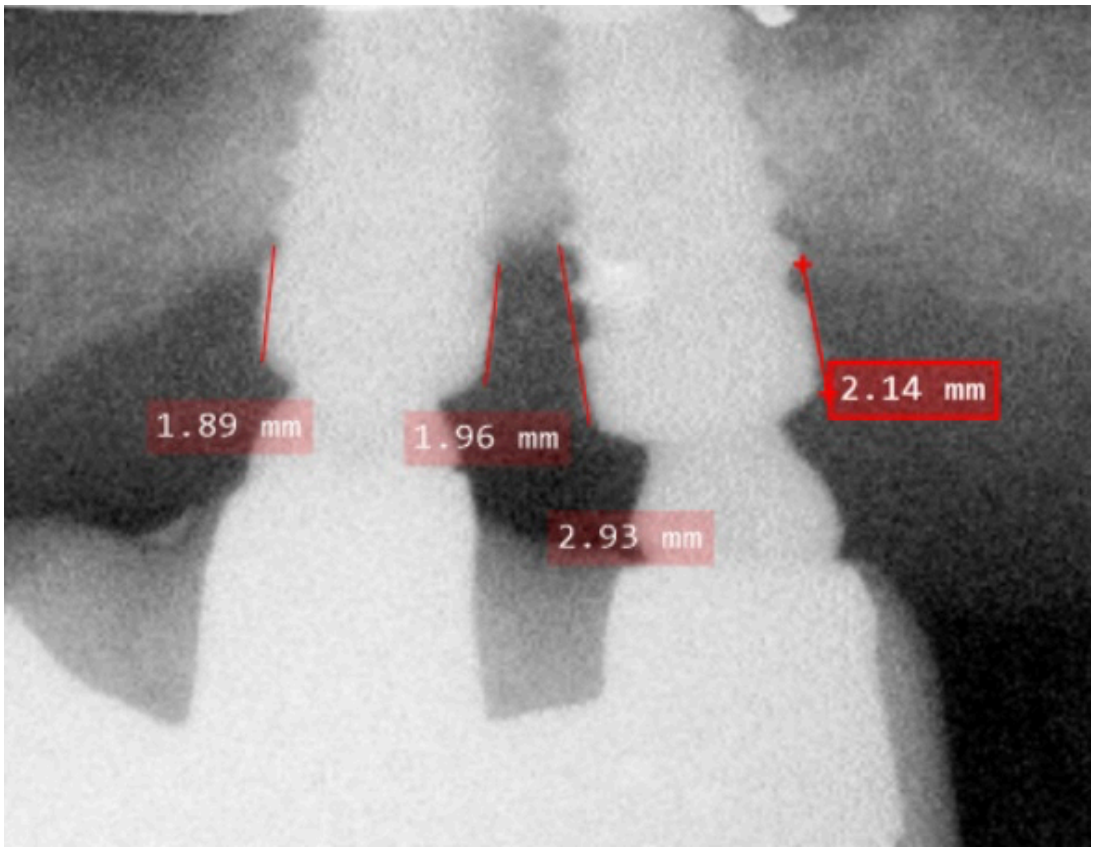
Radiographic evaluation was performed for all patients included in the study in order to assess peri-implant marginal bone level changes over time. Standardized radiographic measurements were obtained at baseline (T0) and at the 5-year follow-up.

For each patient, the marginal bone levels were measured on both the mesial and distal aspects of the implant. Measurements were performed using calibrated digital radiographs and expressed in millimeters (mm). Mesial and distal bone level values were recorded separately at each time point in order to evaluate peri-implant bone remodeling over time.

Radiographic measurements were performed using the ImageJ® software (National Institutes of Health, Bethesda, MD, USA; https://imagej.net/ij/)**.** For each radiograph, implant length were used as radiographic reference parameters for image calibration and measurement standardization, allowing accurate and reproducible linear measurements.

Subsequently, the mean bone level for each patient was calculated as the average of the mesial and distal measurements. Marginal bone loss (MBL) was then determined by calculating the difference between baseline bone level values and those recorded at the 5-year follow-up (T0 – 5-year follow-up).

After calculating individual MBL values, mean MBL and standard deviation (SD) were calculated for each study group. These values were subsequently used for statistical analysis and intergroup comparison between the collagen membrane group and the pericardium membrane group.



Representative radiographic measurement of peri-implant marginal bone levels performed using the ImageJsoftware. Mesial and distal bone levels were measured on calibrated digital radiographs at baseline (T0) and at the 5-year follow-up. Implant length and implant diameter were used as reference parameters for radiographic calibration and standardization of linear measurements.

2.5 Statistical analysis

Statistical analyses were performed using Microsoft Excel® (Microsoft Corporation, Redmond, WA, USA) and Python® (Python Software Foundation, Wilmington, DE, USA). Microsoft Excel® was used for data collection, database organization, and calculation of descriptive statistics, including:

- sample size (n)
- mean marginal bone loss (MBL)
- standard deviation (SD).

Inferential statistical analyses were conducted in Python® using the SciPy, NumPy, and Matplotlib libraries. Differences in MBL between the collagen membrane group and the

pericardium membrane group were assessed using Welch's independent samples t-test (SciPy library), which was selected because it does not assume equal variances between groups. The following parameters were obtained from the Welch's independent samples t-test:

- test statistic (t),
- degrees of freedom (df),
- p-value.

In addition, Cohen's d effect size and 95% confidence intervals (95% CI) were calculated using Pyton to evaluate the magnitude and clinical relevance of the observed differences between groups. Statistical significance was established at $p < 0.05$.

The following statistical hypotheses were tested:

- Null hypothesis (H0): there is no statistically significant difference in mean MBL values between the two groups.
- Alternative hypothesis (H1): there is a statistically significant difference in mean MBL values between the two groups.

To provide a graphical representation of data distribution and variability within the two groups, a boxplot visualization was additionally performed using the Matplotlib library.

3. RESULTS

3.1 Marginal Bone Loss (MBL)

A total of 53 patients were included in the radiographic analysis of marginal bone loss (MBL), with 29 patients allocated to the collagen membrane group and 24 patients allocated to the pericardium membrane group. All patients completed the 5-year follow-up and presented radiographs of sufficient quality for standardized radiographic evaluation.

The collagen membrane group included patients ranging in age from 43 to 86 years, while the pericardium membrane group included patients aged between 50 and 85 years. The demographic characteristics of the study population are summarized in Table 1.

Variable	**Collagen Membrane Group (n= 29)**	**Pericardium Membrane Group (n= 24)**
Male, n (%)	12 (41.4%)	11 (45.8%)
Female, n (%)	17 (58.6%)	13 (54.2%)
Mean Age (years)	68.4	64.3

Table 1. Demographic characteristics of the patients included in the two study groups.

The collagen membrane group showed a mean MBL value of 1.285 ± 0.946 mm. Individual MBL values ranged from -0.25 mm to 3.41 mm, demonstrating moderate variability in peri-implant bone remodeling among patients.

The pericardium membrane group showed a mean MBL value of 1.324 ± 1.046 mm. Individual MBL values ranged from 0 mm to 3.27 mm. Similarly to the collagen membrane group, a certain degree of inter-patient variability was observed. MBL values in the two study groups are reported in Table 2.

Comparison between the two groups was performed using Welch's independent samples t-test. Statistical analysis demonstrated no statistically significant difference in mean MBL values between the collagen membrane group and the pericardium membrane group ($t = -0.1430$; $df \approx 47$; $p = 0.8869$). The mean difference between groups

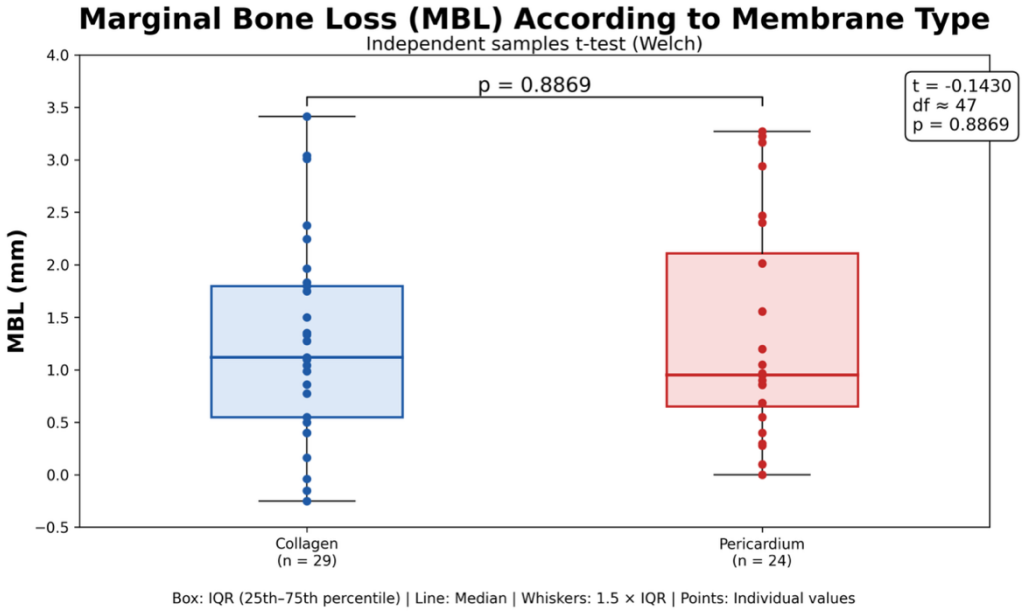
was -0.0395 mm (95% CI: -0.596 to 0.517 mm). Cohen's d was -0.040, indicating a negligible effect size and confirming the absence of a clinically relevant difference between the two membrane types.

Group	N	Mean MBL (mm)	SD	p-value
collagen membrane	29	1.285	0.946	0.8869
pericardium membrane	24	1.324	1.046	

Table 2. Statistical comparison between groups

The difference between the mean MBL values of the two groups was minimal (Δ = -0.0395 mm), indicating comparable peri-implant bone stability over the 5-year follow-up period regardless of the membrane type used.

To provide a graphical representation of data distribution and variability within the two groups, boxplot visualization was performed using the Matplotlib library, as shown in the figure below.



Boxplot showing marginal bone loss (MBL) values in the collagen membrane group (n = 29) and the pericardium membrane group (n = 24). Boxes represent the interquartile range (IQR), the horizontal line indicates the median, and whiskers represent 1.5 × IQR. Individual patient values are displayed as dots. Welch's independent samples t-test demonstrated no statistically significant difference between groups (t

= -0.1430; df ≈ 47; p = 0.8869), indicating comparable peri-implant bone stability between the two membrane types over the 5-year follow-up period.

A descriptive subgroup analysis was additionally performed according to sex and age (<65 and ≥65 years). In the collagen membrane group, mean MBL values were 1.203 ± 0.875 mm in females and 1.400 ± 1.068 mm in males. In the pericardium membrane group, mean MBL values were 1.266 ± 1.098 mm in females and 1.441 ± 0.993 mm in males.

When stratified by age, patients younger than 65 years showed mean MBL values of 1.268 ± 0.811 mm and 1.199 ± 1.059 mm in the collagen and pericardium membrane groups, respectively. Patients aged 65 years or older showed mean MBL values of 1.293 ± 1.032 mm and 1.473 ± 1.061 mm, respectively. All subgroup results according to sex and age are reported in Table 3.

Variable	Collagen Membrane Group	Pericardium Membrane Group
Female MBL (mm) mean ± SD	1.203 ± 0.875	1.266 ± 1.098
Male MBL (mm) mean ± SD	1.400 ±1.068	1.441 ± 0.9993
MBL < 65 years (mm) mean ± SD	1.268 ± 0.811	1.199 ± 1.059
MBL > 65 years (mm) mean ± SD	1.293 ±1.032	1.473 ± 1.061

Table 3. Descriptive subgroup analysis of MBL according to sex and age group.

Overall, no evident differences in MBL were observed according to sex or age category within either treatment group.

3.2 Implant failure

No implant failures were recorded during the 5-year follow-up period in either group. Consequently, implant survival was 100% in both the collagen membrane group (29/29 implants) and the pericardium membrane group (24/24 implants). Due to the absence of failures, no statistical comparison between groups was performed.

3.3 Gingival Inflammation Index

The qualitative assessment of peri-implant soft tissue health using the Gingival Inflammation Index revealed the absence of clinically relevant inflammatory signs in both study groups. No statistically significant differences were observed between the collagen membrane group and the pericardium membrane group, indicating favorable long-term peri-implant soft tissue conditions.

4. DISCUSSION

4.1 Collagen Membranes

4.1.1 General Considerations

Collagen membranes are currently considered the gold standard among resorbable barrier membranes used in guided bone regeneration (GBR) procedures. Their widespread clinical use is supported by extensive evidence demonstrating predictable regenerative outcomes, excellent biocompatibility, and favorable long-term implant performance. The biological rationale underlying their use is based on the principles of GBR, whereby the membrane acts as a selective barrier, preventing the migration of epithelial and connective tissue cells into the defect while allowing osteogenic cells to repopulate the regenerative area and promote new bone formation. [60,81]

Several biological advantages of collagen membranes have been described in the literature. Due to their natural origin, collagen membranes exhibit excellent tissue compatibility, promote angiogenesis and clot stabilization, and facilitate soft tissue healing. Furthermore, their resorbable nature eliminates the need for a second surgical procedure for membrane removal, thereby reducing patient morbidity and postoperative discomfort. [60,82] These characteristics contribute to the creation of a favorable regenerative environment and may partially explain the predictable outcomes reported in numerous clinical studies.

The regenerative potential of collagen membranes has been extensively documented in both horizontal and vertical ridge augmentation procedures. Wessing et al., in a systematic review and meta-analysis, concluded that GBR performed with collagen membranes and particulate graft materials represents a predictable and effective treatment modality for alveolar ridge reconstruction, resulting in substantial bone gain and high implant survival rates.[83] Similarly, Khojasteh et al. reported that collagen membranes are associated with significant horizontal and vertical bone regeneration in alveolar defects. The studies included in their review demonstrated horizontal ridge augmentation

frequently exceeding 5 mm and vertical bone gain ranging from approximately 3.5 mm to more than 8 mm.[84]

Overall, the available literature suggests that collagen membranes provide a stable regenerative environment capable of supporting both horizontal and vertical bone regeneration, making them a predictable treatment option in the management of complex alveolar defects.

4.1.2 Marginal Bone Loss and Collagen membrane

Although most studies evaluating collagen membranes have primarily focused on bone gain and implant survival, several investigations have also assessed peri-implant marginal bone stability after functional loading. Marginal bone loss (MBL) is considered one of the most relevant indicators of long-term implant success, as it reflects the ability of regenerated bone to maintain stable peri-implant conditions over time.

The results of the present study demonstrated a mean marginal bone loss of 1.285 ± 0.946 mm after 5 years in the collagen membrane group. These findings are remarkably consistent with those reported by Meloni et al., who evaluated implants placed in horizontally augmented ridges reconstructed using a native collagen membrane combined with a mixture of autogenous bone and xenograft particles. After five years of functional loading, the authors reported a mean MBL of 1.29 mm, a value almost identical to that observed in the present investigation. [85] The striking similarity between the two studies further supports the long-term stability of regenerated bone obtained through collagen membrane-assisted GBR procedures. Similarly, Pisano et al., who reported a mean MBL of approximately 0.8 ± 0.29 mm after six years following horizontal GBR performed with autogenous bone, anorganic bovine bone, and collagen membranes.[86]

Additional evidence supporting the long-term stability of collagen membrane-assisted regenerative procedures was provided by Beretta et al., who evaluated implants placed in alveolar sockets preserved using demineralized bovine bone mineral covered with a collagen matrix. After 5 years of follow-up, marginal bone resorption remained extremely limited, reaching 0.15 ± 0.17 mm at the mesial aspect and 0.11 ± 0.14 mm at the distal aspect. No significant changes in peri-implant bone levels were observed over

time, confirming the long-term stability of the regenerated hard and soft tissues. [87] Although the marginal bone loss reported by Beretta et al. was lower than that observed in the present study, direct comparison should be interpreted with caution, since their investigation evaluated alveolar socket preservation procedures, whereas the present study included Class II and III alveolar bone defects requiring more extensive guided bone regeneration procedures.

Importantly, despite the complexity of the defects included in the present cohort, the MBL observed after 5 years remained within the range reported by previous long-term studies evaluating implants placed in regenerated bone. The close agreement with the results reported by Meloni et al. is particularly noteworthy, as both investigations evaluated regenerated sites over the same observation period. Furthermore, no evidence of excessive peri-implant bone loss was observed, suggesting that collagen membranes were able to provide a stable regenerative environment capable of maintaining peri-implant bone support over time.

From a clinical perspective, the maintenance of marginal bone levels after 5 years is particularly relevant in Class II and III alveolar bone defects, where the amount of regenerated bone is often greater and the regenerative challenge more demanding than in socket preservation procedures. Therefore, the results of the present study support the long-term predictability of collagen membrane-assisted GBR procedures and confirm that regenerated bone can provide stable support for implant function even in complex clinical situations.

4.1.3 Implant Survival and Collagen Membranes

In addition to promoting bone regeneration, collagen membranes have been associated with high implant survival rates in regenerated sites. Their ability to stabilize graft materials, maintain the regenerative space, and prevent soft tissue invasion contributes to the formation of an adequate bone volume capable of supporting long-term implant function. Consequently, implant survival has frequently been used as a key indicator of the clinical success of collagen membrane-assisted guided bone regeneration (GBR) procedures.

The results of the present study demonstrated a 100% implant survival rate in the collagen membrane group after 5 years of follow-up. Despite the complexity of the Class II and III alveolar bone defects included in the present cohort, no implant failures were recorded during the observation period. These findings suggest that collagen membrane-assisted GBR procedures are capable of creating a stable regenerative environment that effectively supports long-term osseointegration and implant function.

These results are consistent with those reported in the literature. Meloni et al. evaluated 55 implants placed in horizontally augmented ridges reconstructed using a native collagen membrane combined with autogenous bone and anorganic bovine bone mineral. After 5 years of functional loading, neither implant nor prosthetic failures were observed, resulting in an implant survival rate of 100%. [85] Similarly, Pisano et al. assessed 63 implants placed simultaneously with GBR procedures performed using collagen membranes and reported no implant failures after 3 years of follow-up, corresponding to an implant survival rate of 100%.[86] Although minor complications, such as early membrane exposure, occurred in a limited number of cases, implant function and peri-implant health remained stable throughout the observation period.

Overall, the available literature and the findings of the present investigation indicate that collagen membranes represent a reliable regenerative option for the treatment of Class II and III alveolar bone defects. The 100% implant survival rate observed in the present study, identical to that reported by Meloni et al. and comparable to the results described by Pisano et al., further confirms the predictability of collagen membrane-assisted GBR procedures and supports their role as the gold standard among resorbable membranes used in regenerative implant therapy.

4.2 Pericardium Membranes

4.2.1 General Considerations

Pericardium membranes represent an increasingly used alternative among resorbable barrier membranes in guided bone regeneration (GBR) procedures. Derived from pericardial tissue, they are characterized by a dense collagen fiber network that provides favorable mechanical properties, prolonged barrier function, and excellent biocompatibility. Compared with conventional collagen membranes, pericardium membranes exhibit a slower degradation profile, which may contribute to improved maintenance of the regenerative space during healing.[82]

Several clinical studies have demonstrated the effectiveness of pericardium membranes in alveolar ridge augmentation procedures. Sterio et al., in a prospective multicenter study, reported a mean clinical horizontal ridge width gain of 2.61 mm and a radiographic gain ranging from 1.65 to 1.93 mm following GBR performed with a pericardium membrane and particulate allografts. Furthermore, 86.4% of the treated sites achieved sufficient bone volume for implant placement, confirming the regenerative potential of this biomaterial. [88]

Similarly, Lin et al. evaluated 29 patients undergoing horizontal bone augmentation in the anterior aesthetic region and reported an increase in labial bone thickness exceeding 3 mm immediately after surgery. The augmented bone volume remained stable after 6 months of healing, with labial bone thickness values greater than 3 mm maintained at 3–5 mm apical to the implant shoulder. No postoperative complications, such as infection or wound dehiscence, were observed during the follow-up period. [89]

Taken together, these findings suggest that pericardium membranes provide favorable biocompatibility, effective space maintenance, and predictable bone regeneration. Such characteristics may be particularly advantageous in the treatment of Class II and III alveolar bone defects, where maintenance of the regenerative compartment is essential for successful bone reconstruction.

4.2.2 Marginal Bone Loss and Pericardium Membranes

Marginal bone loss (MBL) is considered one of the most important indicators of long-term implant success, as it reflects the stability of peri-implant hard tissues over time. However, compared with conventional collagen membranes, limited evidence is available regarding peri-implant bone stability following the use of pericardium-derived membranes.

The strongest evidence currently available regarding peri-implant bone stability associated with pericardium membranes derives from the randomized controlled trial conducted by Merli et al. The authors compared the use of a pericardium membrane with a conventional collagen membrane in a horizontal ridge augmentation procedure. After 12 months, the pericardium membrane group exhibited significantly lower peri-implant bone loss compared with the collagen membrane group, with a mean difference of 0.24 mm favoring pericardium membranes ($P = 0.0464$). [90] In the subsequent 3-year follow-up, peri-implant bone loss remained lower in the pericardium group (1.02 mm) than in the collagen membrane group (1.61 mm), although the difference was no longer statistically significant. Importantly, no implant failures were recorded during the observation period.[91]

Similar findings were reported by Poli et al., who observed a mean MBL of 0.54 ± 0.70 mm after one year of functional loading in sites regenerated with pericardium membranes. [92] Likewise, Fu et al. reported mesial and distal bone loss values of 0.89 ± 0.72 mm and 1.44 ± 0.71 mm, respectively, after one year, while all implants remained successfully osseointegrated.[93]

In the present study, the mean MBL observed in the pericardium membrane group was 1.324 ± 1.046 mm after 5 years of follow-up. Although this value was higher than those reported in studies with shorter observation periods, it appears consistent with the physiological remodeling process that occurs around dental implants over time. Indeed, peri-implant bone remodeling is expected following implant placement and functional loading, particularly during the first years after prosthetic rehabilitation, after which bone levels generally tend to stabilize.

The available literature demonstrates a progressive increase in MBL with longer follow-up periods. Poli et al. reported a mean MBL of 0.54 ± 0.70 mm after one year of functional loading, whereas Merli et al. observed a mean peri-implant bone loss of approximately 1.02 mm after 3 years in sites regenerated using pericardium membranes. In the present study, the mean MBL reached 1.324 mm after 5 years, suggesting that the increase in marginal bone loss over time occurs gradually and remains within the range generally considered compatible with long-term implant success.

The MBL values observed in the present investigation were comparable to those reported in other long-term studies evaluating implants placed in regenerated bone. Considering the complexity of the Class II and III alveolar bone defects included in the present cohort, the maintenance of stable peri-implant bone levels over a 5-year period may be regarded as a favorable clinical outcome. These findings support the hypothesis that pericardium membranes are capable of providing a stable regenerative environment, promoting bone regeneration while preserving peri-implant tissue stability over time.

4.2.3 Implant Survival and Pericardium Membranes

In addition to maintaining peri-implant bone stability, pericardium membranes have been associated with high implant survival rates following guided bone regeneration (GBR) procedures. Their dense collagen structure and prolonged barrier function may contribute to the creation of a stable regenerative environment capable of supporting long-term osseointegration and implant function.

Although the available literature is more limited than that concerning conventional collagen membranes, the clinical studies published to date have consistently reported favorable implant survival outcomes. Merli et al., in a randomized controlled trial comparing a pericardium membrane with a conventional collagen membrane for horizontal ridge augmentation, reported no implant failures during the first year of follow-up.[90] These findings were confirmed in the subsequent 3-year post-loading evaluation of the same cohort, in which all implants remained functional and no differences in implant survival were observed between the two treatment groups.[91]

Similarly, Poli et al. evaluated implants placed in sites regenerated using a natural collagen pericardium membrane and reported a 100% implant survival rate after one year of functional loading. In addition to the absence of implant failures, favorable peri-implant clinical parameters and limited marginal bone loss were observed, supporting the biological stability of the regenerated tissues.[92]

The results of the present study are consistent with these findings. No implant failures were recorded in the pericardium membrane group during the 5-year follow-up period, resulting in an implant survival rate of 100%. Despite the complexity of the Class II and III alveolar bone defects included in the present cohort, all implants remained functional throughout the observation period. This finding suggests that the regenerated bone obtained using pericardium membranes was able to provide adequate support for long-term osseointegration and implant function.

4.3 Comparison Between Collagen and Pericardium Membranes

4.3.1 Biological Properties

Resorbable membranes play a fundamental role in guided bone regeneration (GBR) procedures, as they provide a barrier between the bone defect and the surrounding soft tissues, thereby promoting the selective repopulation of the defect by osteogenic cells. Among the available resorbable membranes, collagen membranes have long been considered the gold standard due to their excellent biocompatibility, favorable handling characteristics, and extensive clinical documentation. More recently, pericardium-derived membranes have gained increasing attention as an alternative regenerative material because of their specific structural and biological properties.

From a biological perspective, both membrane types are primarily composed of collagen and share several characteristics, including biocompatibility, low immunogenicity, and the ability to support angiogenesis and tissue healing. However, important structural differences exist between them. Conventional collagen membranes

are generally characterized by a more rapid degradation profile, which may reduce the duration of the barrier effect during healing. In contrast, pericardium membranes exhibit a denser and more organized collagen fiber architecture, resulting in greater mechanical resistance and a slower resorption rate. Consequently, pericardium membranes may maintain the regenerative space and barrier function for a longer period, theoretically providing a more favorable environment for bone regeneration in complex defects.[82]

4.3.2 Comparison of Marginal Bone Loss

Several studies have investigated the clinical performance of both membrane types. In particular, the randomized controlled trial conducted by Merli et al. directly compared a pericardium membrane with a conventional collagen membrane during horizontal ridge augmentation procedures. The authors reported significantly lower peri-implant bone loss in the pericardium group after one year, suggesting a potential advantage of the prolonged barrier function provided by the pericardium membrane.[90] Nevertheless, the subsequent 3-year follow-up demonstrated that although marginal bone loss remained lower in the pericardium group, the difference was no longer statistically significant.[91] These findings suggest that the theoretical biological advantages of pericardium membranes may not necessarily translate into substantial long-term clinical differences.

The results of the present study are in agreement with this observation. Although the two membrane types differ in their structural characteristics and degradation kinetics, no statistically significant differences were found between the collagen and pericardium groups with respect to marginal bone loss after 5 years of follow-up. The mean MBL was 1.285 ± 0.946 mm in the collagen membrane group and 1.324 ± 1.046 mm in the pericardium membrane group, with no statistically significant difference between groups ($p = 0.8869$). These findings indicate that both membrane types were capable of maintaining stable peri-implant bone levels over time and suggest that the biological differences between the materials did not significantly influence long-term peri-implant bone remodeling.

The absence of significant differences becomes even more relevant when considering the complexity of the defects included in the present investigation. All patients presented with Class II or Class III alveolar bone defects, conditions that are generally associated with greater regenerative challenges and increased risk of dimensional changes during healing. Despite these challenging conditions, both membrane types achieved comparable outcomes in terms of peri-implant marginal bone stability throughout the observation period, confirming their effectiveness in maintaining regenerated bone volume and peri-implant tissue stability.

4.3.3 Comparison of Implant Survival

A similar trend was observed when implant survival was considered. The available literature consistently reports high implant survival rates following GBR procedures performed with either collagen or pericardium membranes. Meloni et al. and Pisano et al. reported implant survival rates of 100% in regenerated sites treated with collagen membranes, [85,86] while Merli et al., Poli et al., and Fu et al. observed equally favorable outcomes in sites treated with pericardium membranes.[90-93] Consistent with these findings, no implant failures were recorded in either group in the present study, resulting in a cumulative implant survival rate of 100% after 5 years of follow-up.

These results suggest that both membrane types were capable of creating and maintaining a regenerative environment adequate for successful osseointegration and long-term implant function. Although pericardium membranes may theoretically provide a more prolonged barrier effect due to their slower degradation, this characteristic did not result in superior implant survival or improved peri-implant bone stability compared with collagen membranes. Likewise, the faster resorption profile of conventional collagen membranes did not appear to compromise regenerative outcomes or long-term implant success.

4.4 Clinical Implications

From a clinical standpoint, the findings of the present study suggest that the choice between collagen and pericardium membranes should not be based exclusively on expectations of improved peri-implant bone stability or implant survival. Since both membrane types demonstrated comparable long-term outcomes, other factors may play a more relevant role in membrane selection, including handling properties, mechanical characteristics, surgeon preference, defect morphology, availability, and economic considerations.

Overall, the results of the present investigation indicate that both collagen and pericardium membranes represent predictable and reliable treatment options for GBR procedures in Class II and III alveolar bone defects. Despite their biological and structural differences, both materials achieved similar levels of marginal bone stability and identical implant survival rates after 5 years of follow-up. Therefore, within the limitations of the present study, neither membrane demonstrated a clear clinical advantage over the other, supporting the use of both materials in the regenerative management of complex alveolar defects.

4.5 Limitations of the Study

The present study has several limitations that should be considered when interpreting the results. First, its retrospective design inherently carries the risk of selection bias and limits the ability to establish causal relationships between the type of membrane used and the clinical outcomes observed.

Second, the sample size was relatively limited, comprising 53 patients overall. Although the study was able to provide valuable long-term clinical data, a larger cohort would increase the statistical power and improve the generalizability of the findings.

Another limitation is related to the radiographic assessment. Some baseline radiographs (T0) were originally acquired in analog format and were subsequently digitized and

calibrated prior to measurement. Although all images were standardized and analyzed using a validated calibration protocol, it cannot be excluded that the digitization process introduced minor image distortion or measurement inaccuracies, potentially representing a source of bias.

Furthermore, the study population included a certain degree of heterogeneity in both defect characteristics and anatomical locations. Class II and Class III alveolar bone defects were included, and regenerative procedures were performed in both the maxilla and the mandible. Since bone morphology, density, and healing patterns may differ between defect types and jaw locations, these factors could have influenced the clinical outcomes.

Finally, although the present study included the evaluation of peri-implant marginal bone loss, implant survival, and gingival inflammation, other potentially relevant outcomes, such as patient-reported outcome measures (PROMs), aesthetic parameters, and histological assessments, were not available. The inclusion of these variables could have provided a more comprehensive evaluation of the regenerative performance of the two membrane types.

Despite these limitations, the present study provides valuable long-term data with a 5-year follow-up and represents one of the few investigations directly comparing collagen and pericardium membranes in the treatment of Class II and III alveolar bone defects.

5. CONCLUSION

The reconstruction of Class II and III alveolar bone defects remains one of the most challenging procedures in implant dentistry, requiring the achievement of adequate bone regeneration together with the long-term maintenance of peri-implant tissue stability.

The present retrospective study evaluated the long-term outcomes of guided bone regeneration performed using collagen membranes and pericardium membranes in the treatment of Class II and III alveolar bone defects. After 5 years of follow-up, both membrane types demonstrated favorable clinical and radiographic outcomes. No implant failures were recorded in either group, resulting in an implant survival rate of 100%, while peri-implant marginal bone levels remained stable over time. Furthermore, no statistically significant differences were observed between the collagen and pericardium membrane groups regarding marginal bone loss, implant survival, or gingival inflammation.

These findings suggest that both collagen and pericardium membranes are capable of providing a stable regenerative environment, supporting successful bone regeneration and long-term implant function even in complex alveolar defects.

Within the limitations of the present study, it can be concluded that both collagen and pericardium membranes represent reliable treatment options for guided bone regeneration in Class II and III alveolar bone defects. Further clinical studies with larger sample sizes and longer follow-up periods are required to confirm these findings and to further clarify the potential advantages of each membrane type in specific clinical situations.

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