

Comparative Evaluation of Guided Bone Regeneration Using Different Barrier Membranes Around Dental Implants

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Aim:

To compare the clinical and radiographic outcomes of guided bone regeneration performed using collagen membranes and expanded polytetrafluoroethylene (ePTFE) membranes in patients undergoing dental implant therapy.

Materials & Methods:

This prospective comparative clinical study included 40 patients requiring guided bone regeneration in conjunction with dental implant placement. Participants were equally allocated into two groups: Group I received a collagen membrane (n = 20), while Group II received an ePTFE membrane (n = 20). Clinical outcomes assessed included ISQ, soft tissue healing, membrane exposure, wound dehiscence, postoperative infection, postoperative complications, and implant survival. Radiographic assessments comprised horizontal bone gain, vertical bone gain, and marginal bone loss at scheduled follow-up visits over a 12-month period. Statistical analyses were performed using the independent-samples t-test, paired-samples t-test, repeated-measures Analysis of Variance (ANOVA), and Chi-square/Fisher's exact tests, with statistical significance established at $p < 0.05$.

Results:

The two study groups were comparable at baseline with respect to demographic characteristics, implant site distribution, and alveolar defect morphology ($p > 0.05$). The ePTFE membrane group demonstrated significantly greater horizontal bone gain at 6 months (3.91 ± 0.67 mm vs. 3.42 ± 0.61 mm; $p = 0.020$)

and 12 months (3.82 ± 0.64 mm vs. 3.31 ± 0.58 mm; $p = 0.012$). Likewise, vertical bone gain was significantly greater in the ePTFE group at both 6 months (2.63 ± 0.57 mm vs. 2.18 ± 0.52 mm; $p = 0.013$) and 12 months (2.55 ± 0.54 mm vs. 2.09 ± 0.49 mm; $p = 0.008$). Implant stability improved significantly over time in both groups ($p < 0.001$), with no statistically significant differences between the groups at any follow-up interval ($p > 0.05$). Marginal bone loss remained minimal and comparable throughout the study period. The collagen membrane group demonstrated significantly superior soft tissue healing, with a greater proportion of participants exhibiting excellent healing (80.0% vs. 55.0%; $p = 0.048$). Although membrane exposure, wound dehiscence, postoperative infection, and overall postoperative complications occurred more frequently in the ePTFE group, these differences were not statistically significant ($p > 0.05$). Implant survival was high in both groups, with survival rates of 100% in the collagen membrane group and 95% in the ePTFE membrane group ($p = 1.000$).

Conclusion:

Both collagen and ePTFE membranes proved to be effective barrier membranes for guided bone regeneration associated with dental implant placement, producing favorable clinical and radiographic outcomes. The ePTFE membrane provided superior horizontal and vertical bone augmentation, whereas the collagen membrane was associated with enhanced soft tissue healing and fewer membrane-related complications. Implant stability, marginal bone preservation, and implant survival were comparable between the two treatment modalities. These findings suggest that membrane selection should be individualized according to the regenerative requirements of the defect and the desired soft tissue healing characteristics.

Keywords: Collagen membrane, Dental implants, Expanded polytetrafluoroethylene membrane, Guided bone regeneration, Implant stability, Soft tissue healing

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Introduction

Replacement of missing teeth with dental implants has become a predictable and widely accepted treatment because of its high survival rates, restoration of masticatory function, and favorable esthetic outcomes. Achieving long-term implant success depends largely on the presence of sufficient alveolar bone to ensure primary stability and proper three-dimensional implant positioning. However, physiological bone remodeling after tooth extraction, periodontal destruction, trauma, infection, and other pathological conditions often result in

inadequate bone volume, creating the need for regenerative procedures before or during implant placement. Guided bone regeneration (GBR) has therefore become an indispensable technique in modern implant therapy [1].

It is founded on the concept of separating soft tissues from the underlying bone defect with the aid of a barrier membrane. This selective cell exclusion creates a protected environment in which osteogenic cells can repopulate the defect without competition from rapidly proliferating epithelial and connective tissue cells. By preserving this regenerative space, GBR

promotes predictable new bone formation and enhances the likelihood of successful implant osseointegration [2].

The barrier membrane represents a key component of the GBR procedure because it stabilizes the graft material, maintains the required regenerative space, and minimizes soft tissue infiltration during healing. The ideal membrane should be biocompatible, easy to manipulate surgically, capable of maintaining structural integrity throughout the healing period, and compatible with the surrounding tissues without eliciting adverse inflammatory reactions. Since no currently available membrane satisfies every clinical requirement, the choice of membrane is influenced by defect characteristics and treatment objectives [3].

Barrier membranes used in implant dentistry are generally classified as resorbable or non-resorbable. Resorbable collagen membranes are frequently selected because they integrate well with surrounding tissues, possess favorable biological properties, and gradually degrade without requiring surgical retrieval. These advantages reduce patient morbidity and simplify postoperative management. Nevertheless, their relatively limited mechanical strength and gradual loss of structural stability may reduce their effectiveness in maintaining space within extensive or complex bone defects [4].

Non-resorbable membranes, particularly expanded polytetrafluoroethylene (ePTFE), provide greater rigidity and superior maintenance of regenerative space, making them suitable for defects that demand prolonged structural support. Their ability to preserve the grafted area has been associated with substantial bone regeneration in numerous clinical situations. However, membrane exposure remains a recognized complication, and the requirement for a second surgical procedure for membrane removal may increase treatment complexity and patient discomfort [5].

Both collagen and ePTFE membranes have demonstrated encouraging clinical outcomes in GBR yet published evidence continues to report

differences in regenerative capacity, complication rates, and clinical handling. Factors including membrane design, graft material, defect morphology, surgical technique, and patient-related variables may influence treatment outcomes. Consequently, identifying the most appropriate membrane for specific clinical situations remains an important area of investigation [6].

Advances in diagnostic imaging, particularly cone-beam computed tomography (CBCT), have improved the assessment of regenerative outcomes by enabling accurate measurement of horizontal and vertical bone augmentation as well as peri-implant marginal bone changes. In addition, implant stability measurements, healing characteristics, complication rates, and implant survival provide clinically relevant indicators for evaluating the effectiveness of GBR procedures. Together, these parameters allow a comprehensive assessment of both biological regeneration and functional implant success [7].

Continuous innovations in biomaterial science have resulted in the development of enhanced membrane designs with improved mechanical strength, controlled degradation characteristics, and bioactive surface modifications intended to support osteogenesis and tissue healing. Cross-linked collagen membranes, reinforced membrane systems, and biofunctionalized barriers have expanded the therapeutic options available for regenerative implant procedures, although definitive evidence supporting the superiority of one membrane over another remains limited [8].

Although GBR has become a routine procedure in implant dentistry, uncertainty persists regarding the comparative clinical performance of different barrier membranes under similar treatment conditions. Additional comparative studies are therefore necessary to provide stronger evidence for selecting membrane materials that maximize bone regeneration while minimizing complications and patient morbidity [9, 10].

Accordingly, the present study aimed to compare the effectiveness of resorbable collagen

membranes and non-resorbable ePTFE membranes used during GBR around dental implants. Clinical healing, implant stability, radiographic bone gain, peri-implant marginal bone changes, and postoperative complications were evaluated to determine the regenerative performance of each membrane type.

Materials & Methods

Study Design

This prospective randomized clinical investigation was carried out in a single tertiary care centre over an 18-month period. Ethical approval was obtained from the Institutional Ethics Committee before patient recruitment, and the study was conducted in accordance with the principles outlined in the Declaration of Helsinki. All eligible participants received detailed information regarding the study objectives and procedures and provided written informed consent prior to enrollment.

Patient Selection

Forty patients requiring implant-supported rehabilitation with simultaneous GBR for localized peri-implant bone deficiencies were consecutively recruited from the outpatient clinic. All patients underwent comprehensive clinical examination and radiographic assessment before inclusion.

Inclusion Criteria

Participants were considered eligible if they fulfilled the following criteria:

- Age between 20 and 65 years
- Presence of partial edentulism requiring dental implant placement
- Localized horizontal and/or vertical alveolar ridge deficiency necessitating GBR at the time of implant surgery
- Good oral hygiene with a Plaque Index of ≤ 1
- Ability and willingness to attend all scheduled follow-up visits

Exclusion Criteria

- Patients were excluded if they presented with any of the following:

- Systemic disorders known to impair wound healing or bone regeneration
- Smoking habit exceeding 10 cigarettes per day
- Pregnancy or breastfeeding
- Active periodontal disease or untreated oral infection
- Previous radiotherapy to the head and neck region
- Current or previous use of bisphosphonates or other drugs influencing bone metabolism
- Parafunctional habits, poor oral hygiene, or inability to comply with the study protocol

Randomization and Grouping

Following enrollment, participants were randomly allocated into two equal treatment groups using a computer-generated randomization schedule.

- Group I (n = 20): GBR using a resorbable collagen membrane in combination with particulate xenogeneic bone graft.
- Group II (n = 20): GBR using a non-resorbable ePTFE membrane together with the same xenogeneic particulate bone graft.

To minimize operator-dependent variability, all implant surgeries and regenerative procedures were completed by a single experienced dental surgeon using a standardized surgical protocol.

Surgical Protocol

Preoperative planning included clinical evaluation and CBCT to determine implant position and quantify alveolar bone deficiency. Standard preoperative antimicrobial prophylaxis and chlorhexidine mouth rinse were administered according to institutional guidelines.

After achieving adequate local anesthesia, a crestal incision with vertical releasing incisions was made, followed by elevation of a full-thickness mucoperiosteal flap. Implant osteotomies were prepared according to the

manufacturer's recommended drilling sequence, and implants were inserted with satisfactory primary stability.

Residual peri-implant defects were augmented using particulate xenogeneic bone graft material. In the collagen membrane group, the graft was completely covered with a resorbable collagen membrane extending beyond the defect margins to ensure adequate coverage. In the ePTFE group, the grafted site was protected with a non-resorbable ePTFE membrane, which was secured according to the manufacturer's instructions. Primary tension-free wound closure was obtained using interrupted and horizontal mattress sutures.

Postoperative Management

Patients received a standardized postoperative regimen consisting of systemic antibiotics, analgesics, and twice-daily rinsing with 0.12% chlorhexidine gluconate for two weeks. Oral hygiene instructions and dietary recommendations were provided to all participants. Sutures were removed approximately 10–14 days after surgery. In patients treated with ePTFE membranes, membrane retrieval was performed after completion of the recommended healing period.

Clinical Assessment

Clinical evaluations were performed at baseline and subsequently at 1 week, 1 month, 3 months, 6 months, and 12 months following surgery.

The clinical variables recorded included:

- Soft tissue healing
- Membrane exposure
- Wound dehiscence
- Postoperative infection
- Overall postoperative complications
- Implant stability measured using Resonance Frequency Analysis (Implant Stability Quotient (ISQ))
- Implant survival

Radiographic Assessment

CBCT scans were obtained immediately after implant placement (baseline) and repeated at 6

and 12 months. Baseline measurements served as the reference for calculating horizontal bone gain, vertical bone gain, and marginal bone level changes during follow-up.

The following measurements were recorded:

- Horizontal bone gain (mm)
- Vertical bone gain (mm)
- Peri-implant marginal bone level changes (mm)
- Outcome Variables

Primary Outcome

The principal outcome measure was horizontal and vertical bone gain assessed using CBCT at 6 and 12 months.

Secondary Outcomes

- Secondary outcome measures included:
- ISQ
- Changes in peri-implant marginal bone levels
- Soft tissue healing
- Membrane exposure
- Wound dehiscence
- Postoperative infection
- Overall postoperative complications
- Implant survival

Statistical Analysis

The collected data were entered into a Microsoft Excel spreadsheet and subjected to statistical analysis using Statistical Package for the Social Sciences (SPSS), version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean and standard deviation (Mean $\pm$ SD), whereas categorical variables were summarized as frequency and percentage [n (%)]. The normality of continuous data was assessed using the Shapiro–Wilk test. For the comparison of continuous variables between the two independent study groups, including horizontal bone gain, vertical bone gain, ISQ, and marginal bone loss, the independent-samples t-test was used. For intragroup comparisons of horizontal and vertical bone gain between the 6-month and 12-month follow-up intervals, the paired-samples t-test was applied.

Changes in the ISQ across the different follow-up intervals—baseline, 3 months, 6 months, and 12 months—within each study group were analyzed using repeated-measures analysis of variance (repeated-measures ANOVA). Appropriate post-hoc pairwise comparisons were performed when required to identify differences between individual follow-up intervals.

Categorical variables, including demographic characteristics, implant location, type of alveolar bone defect, soft tissue healing, membrane exposure, postoperative complications, wound dehiscence, postoperative infection, and implant survival, were compared between the two study groups using the Chi-square test or Fisher's exact test, as appropriate based on the expected cell frequencies.

All statistical tests were two-tailed, and a p value < 0.05 was considered statistically significant, while $p < 0.001$ was considered highly statistically significant.

Results

The distribution of study participants according to demographic characteristics demonstrated that the two study groups were comparable with respect to both age and gender.

Table 1, Figure 1 & Figure 2 presents the age distribution of the study participants. Among the total of 40 participants, the largest proportion belonged to the 31–40 years age group (32.5%), followed by the 41–50 years and 51–65 years age groups, each comprising 25.0%

of the participants. The 20–30 years age group accounted for 17.5% of the study population.

In Group I (Collagen Membrane), 4 participants (20.0%) were aged 20–30 years, 6 (30.0%) were aged 31–40 years and 5 participants (25.0%) each belonged to the 41–50 years and 51–65 years age groups. Similarly, in Group II (ePTFE Membrane), 3 participants (15.0%) were aged 20–30 years, 7 (35.0%) were aged 31–40 years, and 5 participants (25.0%) each belonged to the 41–50 years and 51–65 years age groups. The difference in age distribution between the two study groups was not statistically significant ($p = 0.953$), indicating comparable age distribution between the groups.

Regarding gender, males constituted the majority of the overall study population, accounting for 23 participants (57.5%), while females accounted for 17 participants (42.5%). In Group I, 11 participants (55.0%) were male and 9 (45.0%) were female, whereas in Group II, 12 participants (60.0%) were male and 8 (40.0%) were female. The difference in gender distribution between the two groups was also not statistically significant ($p = 0.749$).

Overall, the absence of statistically significant differences in age and gender distribution indicates that the Collagen Membrane and ePTFE Membrane groups were demographically comparable at baseline, thereby minimizing the potential influence of demographic differences on the subsequent comparison of clinical and radiographic outcomes.

Table 1: Distribution of Study Participants According to Demographic Characteristics

Demographic characteristic	Group I: Collagen Membrane n (%)	Group II: ePTFE Membrane n (%)	Total n (%)	P value
Age group (years)				
20–30	4 (20.0)	3 (15.0)	7 (17.5)	0.953
31–40	6 (30.0)	7 (35.0)	13 (32.5)	
41–50	5 (25.0)	5 (25.0)	10 (25.0)	
51–65	5 (25.0)	5 (25.0)	10 (25.0)	
Gender				
Male	11 (55.0)	12 (60.0)	23 (57.5)	0.749
Female	9 (45.0)	8 (40.0)	17 (42.5)	

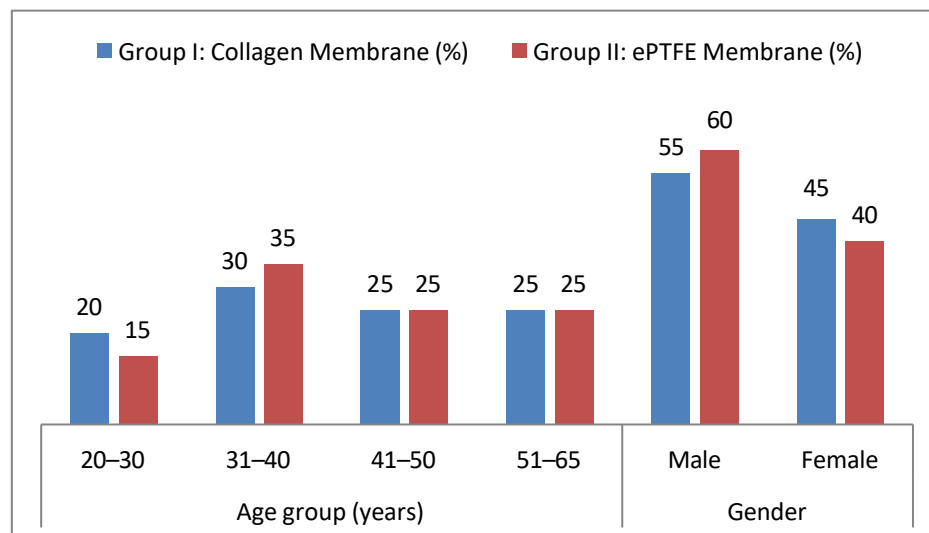


Figure 1: Comparison of Age Distribution Between the Collagen Membrane and ePTFE Membrane Groups

Table 2 & Figure 3 present the distribution of implant sites according to anatomical location and demonstrate a similar pattern between Group I (Collagen Membrane) and Group II (ePTFE Membrane). Among the total of 40 implant sites, the mandibular posterior region was the most common anatomical location, accounting for 13 implants (32.5%), followed by the maxillary posterior region with 12 implants (30.0%), the maxillary anterior region with 9 implants (22.5%), and the mandibular anterior region with 6 implants (15.0%).

In Group I (Collagen Membrane), 5 implants (25.0%) were placed in the maxillary anterior region, 6 (30.0%) in the maxillary posterior region, 3 (15.0%) in the mandibular anterior region, and 6 (30.0%) in the mandibular

posterior region. Similarly, in Group II (ePTFE Membrane), 4 implants (20.0%) were placed in the maxillary anterior region, 6 (30.0%) in the maxillary posterior region, 3 (15.0%) in the mandibular anterior region, and 7 (35.0%) in the mandibular posterior region.

The difference in the distribution of implant sites according to anatomical location between the two study groups was not statistically significant ($p = 0.965$). These findings indicate that the Collagen Membrane and ePTFE Membrane groups were comparable with respect to the anatomical distribution of implant sites, thereby minimizing the potential influence of implant location on subsequent comparisons of clinical and radiographic regenerative outcomes.

Table 2: Distribution of Implant Sites According to Anatomical Location

Implant location	Group I: Collagen Membrane n (%)	Group II: ePTFE Membrane n (%)	Total n (%)	P value
Maxillary anterior	5 (25.0)	4 (20.0)	9 (22.5)	0.965
Maxillary posterior	6 (30.0)	6 (30.0)	12 (30.0)	
Mandibular anterior	3 (15.0)	3 (15.0)	6 (15.0)	
Mandibular posterior	6 (30.0)	7 (35.0)	13 (32.5)	
Total	20 (100.0)	20 (100.0)	40 (100.0)	

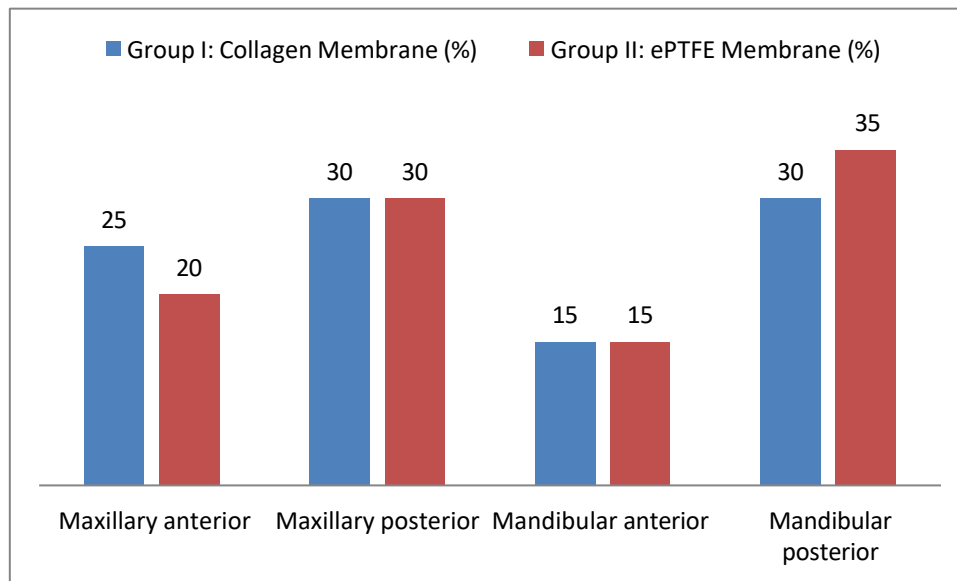


Figure 3: Anatomical Distribution of Implant Sites in the Two Study Groups

Table 3 & Figure 4 present the distribution of participants according to the type of alveolar bone defect and demonstrate a similar pattern between Group I (Collagen Membrane) and Group II (ePTFE Membrane). Among the total of 40 participants, horizontal deficiency was the most commonly observed type of alveolar bone defect, accounting for 23 participants (57.5%), followed by vertical deficiency in 11 participants (27.5%) and combined deficiency in 6 participants (15.0%).

In Group I (Collagen Membrane), horizontal deficiency was observed in 12 participants (60.0%), vertical deficiency in 5 participants (25.0%), and combined deficiency in 3 participants (15.0%). Similarly, in Group II

(ePTFE Membrane), horizontal deficiency was observed in 11 participants (55.0%), vertical deficiency in 6 participants (30.0%), and combined deficiency in 3 participants (15.0%).

The difference in the distribution of alveolar bone defect types between the two study groups was not statistically significant ($p = 0.943$). These findings indicate that the Collagen Membrane and ePTFE Membrane groups were comparable with respect to the baseline distribution of alveolar bone defect types, thereby minimizing the potential influence of defect morphology on subsequent comparisons of regenerative outcomes between the two membrane groups.

Table 3: Distribution of Participants According to Type of Alveolar Bone Defect

Type of bone defect	Group I: Collagen Membrane n (%)	Group II: ePTFE Membrane n (%)	Total n (%)	P value
Horizontal deficiency	12 (60.0)	11 (55.0)	23 (57.5)	0.943
Vertical deficiency	5 (25.0)	6 (30.0)	11 (27.5)	
Combined deficiency	3 (15.0)	3 (15.0)	6 (15.0)	
Total	20 (100.0)	20 (100.0)	40 (100.0)	

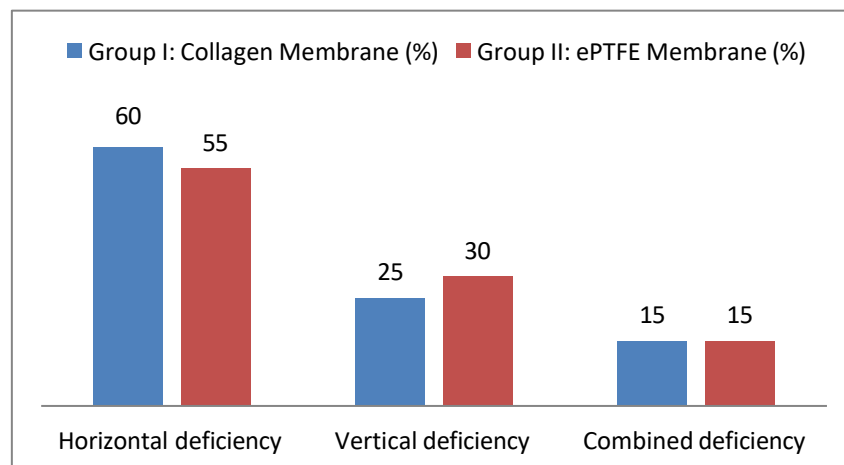


Figure 4: Distribution of Participants According to the Type of Alveolar Bone Defect in Group I (Collagen Membrane) and Group II (ePTFE Membrane)

Table 4 and Figure 5 present the intergroup comparison of horizontal bone gain at different follow-up intervals and demonstrate consistently greater horizontal bone gain in Group II (ePTFE Membrane) than in Group I (Collagen Membrane).

At the 6-month follow-up, the mean horizontal bone gain was 3.42 ± 0.61 mm in the Collagen Membrane group and 3.91 ± 0.67 mm in the ePTFE Membrane group, with a mean difference of 0.49 mm. This difference was statistically significant ($t = 2.42$, $p = 0.020$), indicating significantly greater horizontal bone gain in the ePTFE Membrane group.

Similarly, at the 12-month follow-up, the mean horizontal bone gain was 3.31 ± 0.58 mm in the

Collagen Membrane group, compared with 3.82 ± 0.64 mm in the ePTFE Membrane group. The mean difference of 0.51 mm was also statistically significant ($t = 2.64$, $p = 0.012$), further demonstrating the superior performance of the ePTFE Membrane.

Overall, these findings indicate that the ePTFE Membrane group achieved significantly greater horizontal bone gain than the Collagen Membrane group at both the 6- and 12-month follow-up assessments. Although a slight reduction in horizontal bone gain was observed between the 6- and 12-month evaluations in both groups, the ePTFE Membrane consistently maintained superior horizontal bone dimensions throughout the follow-up period.

Table 4: Intergroup Comparison of Horizontal Bone Gain at Different Follow-up Intervals

Time interval	Group I: Collagen Membrane Mean $\pm$ SD (mm)	Group II: ePTFE Membrane Mean $\pm$ SD (mm)	Mean difference (mm)	t value	P value
6 months	3.42 ± 0.61	3.91 ± 0.67	0.49	2.42	0.020*
12 months	3.31 ± 0.58	3.82 ± 0.64	0.51	2.64	0.012*

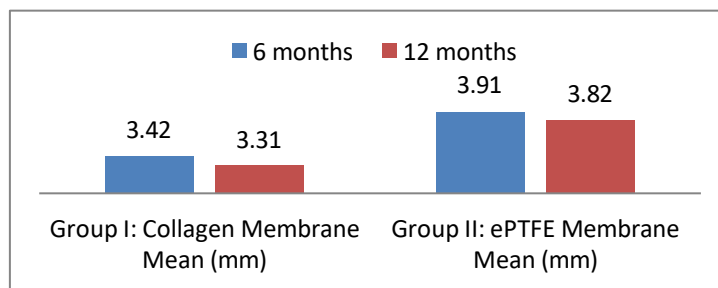


Figure 5: Intergroup Comparison of Horizontal Bone Gain at 6 and 12 Months in the Collagen Membrane and ePTFE Membrane Groups

Table 5 and Figure 6 present the intergroup comparison of vertical bone gain at the 6- and 12-month follow-up intervals. The results indicate that Group II (ePTFE Membrane) consistently achieved greater vertical bone gain than Group I (Collagen Membrane) throughout the study period.

At the 6-month follow-up, the mean vertical bone gain was 2.18 ± 0.52 mm in the Collagen Membrane group and 2.63 ± 0.57 mm in the ePTFE Membrane group. The mean intergroup difference was 0.45 mm, which was statistically significant ($t = 2.60$, $p = 0.013$), indicating superior vertical bone regeneration in the ePTFE Membrane group.

At the 12-month follow-up, the mean vertical bone gain was 2.09 ± 0.49 mm in the Collagen Membrane group, compared with 2.55 ± 0.54 mm in the ePTFE Membrane group. The mean difference of 0.46 mm remained statistically significant ($t = 2.82$, $p = 0.008$), confirming the superior regenerative performance of the ePTFE Membrane.

Overall, the findings suggest that the ePTFE Membrane provided significantly greater vertical bone gain than the Collagen Membrane at both follow-up assessments. Although a slight reduction in vertical bone gain was observed from 6 to 12 months in both groups, the ePTFE Membrane demonstrated better preservation of the regenerated vertical bone over time.

Table 5: Intergroup Comparison of Vertical Bone Gain at Different Follow-up Intervals

Time interval	Group I: Collagen Membrane Mean $\pm$ SD (mm)	Group II: ePTFE Membrane Mean $\pm$ SD (mm)	Mean difference (mm)	t value	P value
6 months	2.18 ± 0.52	2.63 ± 0.57	0.45	2.60	0.013*
12 months	2.09 ± 0.49	2.55 ± 0.54	0.46	2.82	0.008*

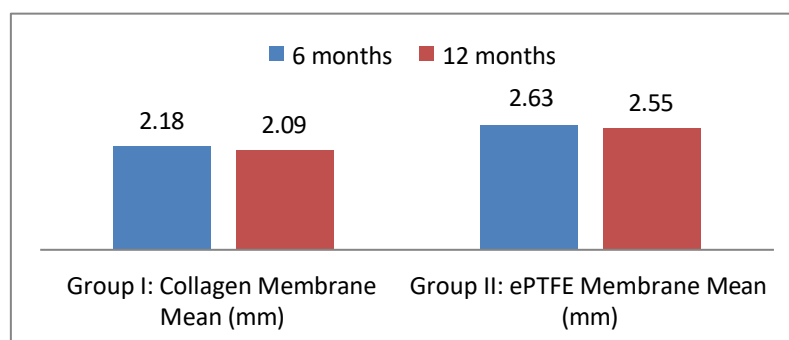


Figure 6: Intergroup Comparison of Vertical Bone Gain at 6 and 12 Months in the Collagen Membrane and ePTFE Membrane Groups

Table 6 & Figure 7 present the intragroup comparison of horizontal bone gain between the 6-month and 12-month follow-up intervals demonstrated a slight reduction in horizontal bone gain over time in both study groups.

In Group I (Collagen Membrane), the mean horizontal bone gain decreased from 3.42 ± 0.61 mm at 6 months to 3.31 ± 0.58 mm at 12 months, representing a mean reduction of 0.11 mm. This reduction was statistically significant (paired $t = 2.17$, $p = 0.043$), indicating a small but significant decrease in the horizontal bone gain between 6 and 12 months.

In Group II (ePTFE Membrane), the mean horizontal bone gain decreased slightly from

3.91 ± 0.67 mm at 6 months to 3.82 ± 0.64 mm at 12 months, corresponding to a mean reduction of 0.09 mm. However, this change was not statistically significant (paired $t = 1.91$, $p = 0.071$), suggesting that the horizontal bone gain achieved with the ePTFE membrane remained relatively stable between the two follow-up intervals.

Overall, both groups demonstrated a slight reduction in horizontal bone gain from 6 to 12 months. However, the reduction was statistically significant only in the Collagen Membrane group, whereas the ePTFE Membrane group showed better maintenance and stability of the achieved horizontal bone gain over time.

Table 6: Intragroup Comparison of Horizontal Bone Gain Between 6 and 12 Months

Group	6 Months Mean $\pm$ SD (mm)	12 Months Mean $\pm$ SD (mm)	Mean change (mm)	Paired t value	P value
Group I: Collagen Membrane	3.42 ± 0.61	3.31 ± 0.58	-0.11	2.17	0.043*
Group II: ePTFE Membrane	3.91 ± 0.67	3.82 ± 0.64	-0.09	1.91	0.071

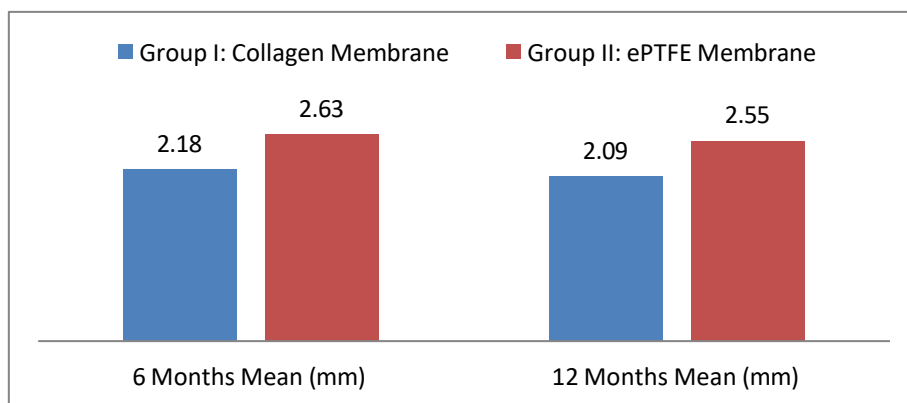


Figure 7: Intragroup Comparison of Horizontal Bone Gain at 6 and 12 Months in the Collagen Membrane and ePTFE Membrane Groups

Table 7 & Figure 8 present the intragroup comparison of vertical bone gain between the 6- and 12-month follow-up intervals and demonstrate a slight reduction in vertical bone gain over time in both study groups.

In Group I (Collagen Membrane), the mean vertical bone gain decreased from 2.18 ± 0.52 mm at 6 months to 2.09 ± 0.49 mm at 12 months, representing a mean reduction of 0.09 mm. This reduction was not statistically

significant (paired $t = 2.05$, $p = 0.054$), although the p value was close to the conventional threshold for statistical significance.

Similarly, in Group II (ePTFE Membrane), the mean vertical bone gain decreased from 2.63 ± 0.57 mm at 6 months to 2.55 ± 0.54 mm at 12 months, corresponding to a mean reduction of 0.08 mm. This change was also not statistically significant (paired $t = 1.82$, $p = 0.085$).

Overall, both the Collagen Membrane and ePTFE Membrane groups demonstrated good maintenance of the achieved vertical bone gain between the 6- and 12-month follow-up assessments, with only minimal reductions over time. As neither intragroup change reached statistical significance, the findings suggest that

vertical bone regeneration remained relatively stable in both groups throughout the follow-up period. Nevertheless, the ePTFE Membrane group consistently exhibited greater absolute vertical bone gain than the Collagen Membrane group at both follow-up intervals.

Table 7: Intragroup Comparison of Vertical Bone Gain Between 6 and 12 Months

Group	6 Months Mean ± SD (mm)	12 Months Mean ± SD (mm)	Mean change (mm)	Paired t value	P value
Group I: Collagen Membrane	2.18 ± 0.52	2.09 ± 0.49	-0.09	2.05	0.054
Group II: ePTFE Membrane	2.63 ± 0.57	2.55 ± 0.54	-0.08	1.82	0.085

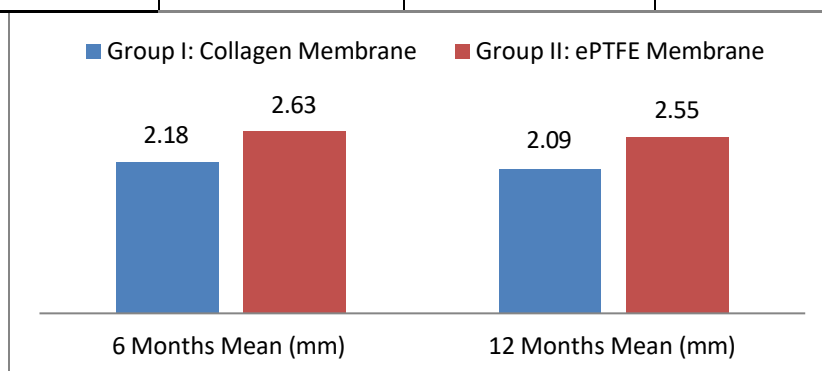


Figure 8: Intragroup Comparison of Vertical Bone Gain at 6 and 12 Months in the Collagen Membrane and ePTFE Membrane Groups

Table 8 & Figure 9 present the intergroup comparison of ISQ values at different follow-up intervals and demonstrate a progressive increase in implant stability over time in both Group I (Collagen Membrane) and Group II (ePTFE Membrane). Although Group II consistently exhibited numerically higher mean ISQ values than Group I, none of the intergroup differences reached statistical significance.

At baseline, the mean ISQ was 67.85 ± 4.62 in the Collagen Membrane group and 68.20 ± 4.47 in the ePTFE Membrane group, with a mean difference of 0.35. This difference was not statistically significant ($t = 0.24$, $p = 0.809$), indicating comparable primary implant stability between the two groups.

At the 3-month follow-up, the mean ISQ increased to 72.40 ± 4.18 in the Collagen Membrane group and 73.65 ± 4.32 in the ePTFE Membrane group. Although the ePTFE

Membrane group demonstrated a higher mean ISQ by 1.25 units, the difference remained statistically non-significant ($t = 0.93$, $p = 0.358$).

At the 6-month follow-up, the mean ISQ further increased to 76.85 ± 3.76 in the Collagen Membrane group and 78.40 ± 3.91 in the ePTFE Membrane group, resulting in a mean difference of 1.55 units. However, this difference was also not statistically significant ($t = 1.28$, $p = 0.208$).

At the 12-month follow-up, the highest mean ISQ values were recorded in both groups, with 79.10 ± 3.52 in the Collagen Membrane group and 80.75 ± 3.68 in the ePTFE Membrane group. The mean difference of 1.65 units was not statistically significant ($t = 1.45$, $p = 0.155$).

Overall, the findings demonstrate a progressive improvement in implant stability from baseline to the 12-month follow-up in both study groups. Although the ePTFE Membrane group

consistently showed numerically higher ISQ values at all assessment points, the differences between the two groups were not statistically significant. These findings suggest that both

Collagen Membrane and ePTFE Membrane treatments were associated with comparable implant stability outcomes during the 12-month follow-up period.

Table 8: Intergroup Comparison of ISQ at Different Follow-up Intervals

Time interval	Group I: Collagen Membrane Mean ± SD	Group II: ePTFE Membrane Mean ± SD	Mean difference	t value	P value
Baseline	67.85 ± 4.62	68.20 ± 4.47	0.35	0.24	0.809
3 months	72.40 ± 4.18	73.65 ± 4.32	1.25	0.93	0.358
6 months	76.85 ± 3.76	78.40 ± 3.91	1.55	1.28	0.208
12 months	79.10 ± 3.52	80.75 ± 3.68	1.65	1.45	0.155

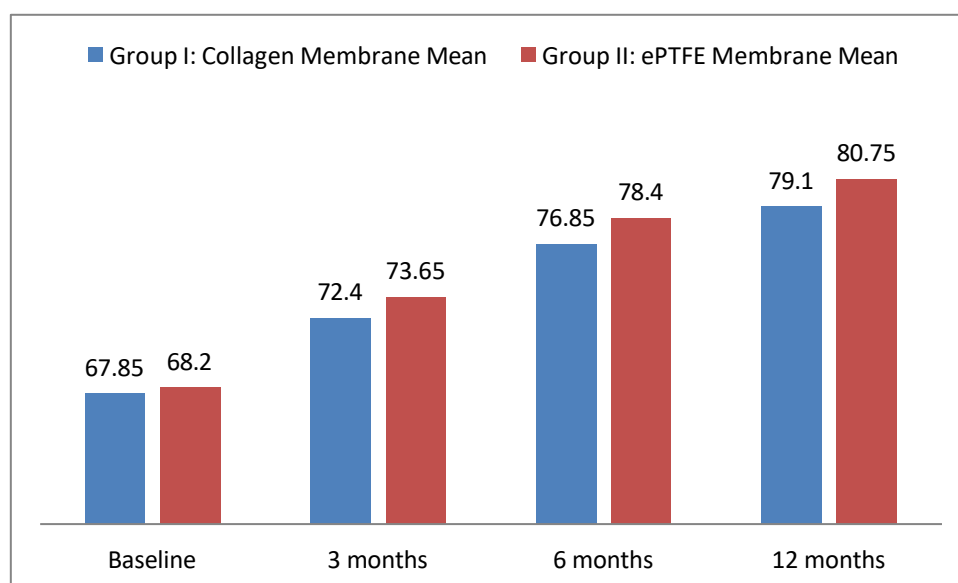


Figure 9: Intergroup Comparison of ISQ Values at Baseline, 3, 6, and 12 Months in the Collagen Membrane and ePTFE Membrane Groups

Table 9 & Figure 10 present the intragroup comparison of ISQ values across different follow-up intervals and demonstrate a progressive and statistically significant increase in implant stability from baseline to 12 months in both Group I (Collagen Membrane) and Group II (ePTFE Membrane).

In Group I (Collagen Membrane), the mean ISQ increased progressively from 67.85 ± 4.62 at baseline to 72.40 ± 4.18 at 3 months, 76.85 ± 3.76 at 6 months, and 79.10 ± 3.52 at 12 months. The overall increase in implant stability across the follow-up period was highly

statistically significant (test statistic = 42.76, $p < 0.001$).

Similarly, in Group II (ePTFE Membrane), the mean ISQ increased from 68.20 ± 4.47 at baseline to 73.65 ± 4.32 at 3 months, 78.40 ± 3.91 at 6 months, and 80.75 ± 3.68 at 12 months. This improvement in implant stability over time was also highly statistically significant (test statistic = 48.21, $p < 0.001$).

Overall, both groups exhibited a significant and consistent increase in implant stability throughout the 12-month follow-up period. Although the ePTFE Membrane group

consistently demonstrated numerically higher mean ISQ values at each assessment interval, the intragroup analysis confirms that implant stability improved significantly over time within

both membrane groups, indicating successful osseointegration and progressive biological stabilization of the implants.

Table 9: Intragroup Comparison of ISQ Over Different Follow-up Intervals

Group	Baseline Mean $\pm$ SD	3 Months Mean $\pm$ SD	6 Months Mean $\pm$ SD	12 Months Mean $\pm$ SD	Test statistic	P value
Group I: Collagen Membrane	67.85 $\pm$ 4.62	72.40 $\pm$ 4.18	76.85 $\pm$ 3.76	79.10 $\pm$ 3.52	42.76	<0.001*
Group II: ePTFE Membrane	68.20 $\pm$ 4.47	73.65 $\pm$ 4.32	78.40 $\pm$ 3.91	80.75 $\pm$ 3.68	48.21	<0.001*

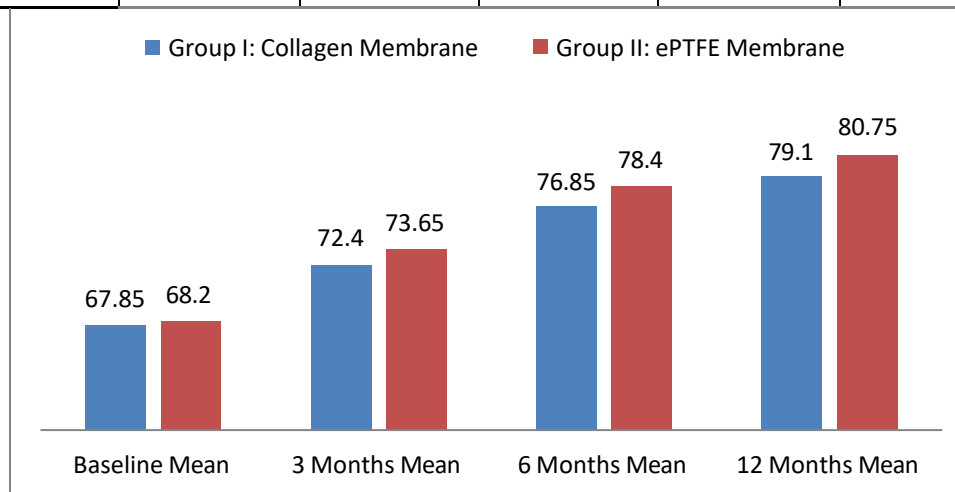


Figure 10: Intragroup Comparison of ISQ Values at Baseline, 3, 6, and 12 Months in the Collagen Membrane and ePTFE Membrane Groups

Table 10 & Figure 11 present the comparison of soft tissue healing outcomes between the two study groups and demonstrate better healing in Group I (Collagen Membrane) than in Group II (ePTFE Membrane).

In the Collagen Membrane group, excellent soft tissue healing was observed in 16 participants (80.0%), while the remaining 4 participants (20.0%) exhibited satisfactory healing. No cases of delayed or compromised healing were recorded in this group.

In contrast, in the ePTFE Membrane group, excellent soft tissue healing was observed in 11 participants (55.0%), whereas 7 participants (35.0%) exhibited satisfactory healing and 2

participants (10.0%) experienced delayed or compromised healing.

Overall, among the 40 participants, 27 (67.5%) demonstrated excellent healing, 11 (27.5%) exhibited satisfactory healing, and only 2 (5.0%) experienced delayed or compromised healing. The difference in soft tissue healing outcomes between the two study groups was statistically significant ($p = 0.048$).

These findings indicate that the Collagen Membrane group achieved significantly better soft tissue healing outcomes than the ePTFE Membrane group, as evidenced by a higher proportion of participants with excellent healing and the absence of delayed or compromised healing.

Table 10: Comparison of Marginal Bone Loss Between the Study Groups

Time interval	Group I: Collagen Membrane Mean $\pm$ SD (mm)	Group II: ePTFE Membrane Mean $\pm$ SD (mm)	Mean difference (mm)	t value	P value
6 months	0.42 $\pm$ 0.18	0.39 $\pm$ 0.16	0.03	0.56	0.581
12 months	0.68 $\pm$ 0.24	0.63 $\pm$ 0.22	0.05	0.69	0.497

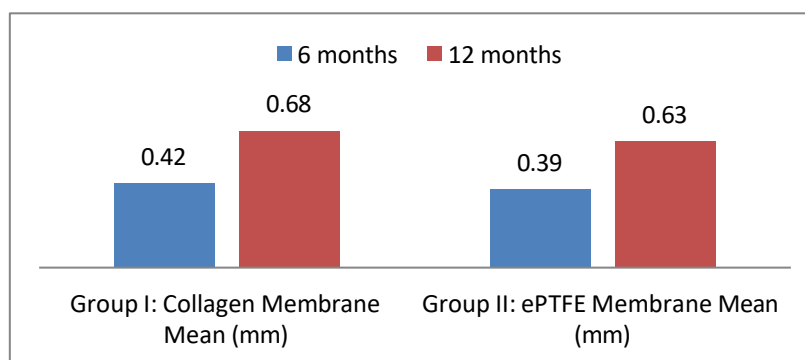
**Figure 11:** Comparison of Soft Tissue Healing Outcomes Between the Collagen Membrane and ePTFE Membrane Groups

Table 11 & Figure 12 present the comparison of soft tissue healing outcomes between Group I (Collagen Membrane) and Group II (ePTFE Membrane). The results indicate more favorable healing outcomes in the Collagen Membrane group than in the ePTFE Membrane group.

In the Collagen Membrane group, 16 participants (80.0%) achieved excellent soft tissue healing, while the remaining 4 participants (20.0%) exhibited satisfactory healing. No participants in this group experienced delayed or compromised healing.

In the ePTFE Membrane group, 11 participants (55.0%) exhibited excellent healing, 7 participants (35.0%) demonstrated satisfactory

healing, and 2 participants (10.0%) showed delayed or compromised healing.

Across all 40 participants, 27 (67.5%) achieved excellent healing, 11 (27.5%) demonstrated satisfactory healing, and 2 (5.0%) experienced delayed or compromised healing. The distribution of healing outcomes differed significantly between the two groups ($p = 0.048$).

Overall, the findings suggest that the Collagen Membrane was associated with more favorable soft tissue healing than the ePTFE Membrane, as reflected by a greater proportion of participants with excellent healing and the absence of delayed or compromised healing in the Collagen Membrane group.

Table 11: Comparison of Soft Tissue Healing Between the Study Groups

Soft tissue healing	Group I: Collagen Membrane n (%)	Group II: ePTFE Membrane n (%)	Total n (%)	P value
Excellent	16 (80.0)	11 (55.0)	27 (67.5)	0.048*
Satisfactory	4 (20.0)	7 (35.0)	11 (27.5)	
Delayed/compromised	0 (0.0)	2 (10.0)	2 (5.0)	
Total	20 (100.0)	20 (100.0)	40(100.0)	

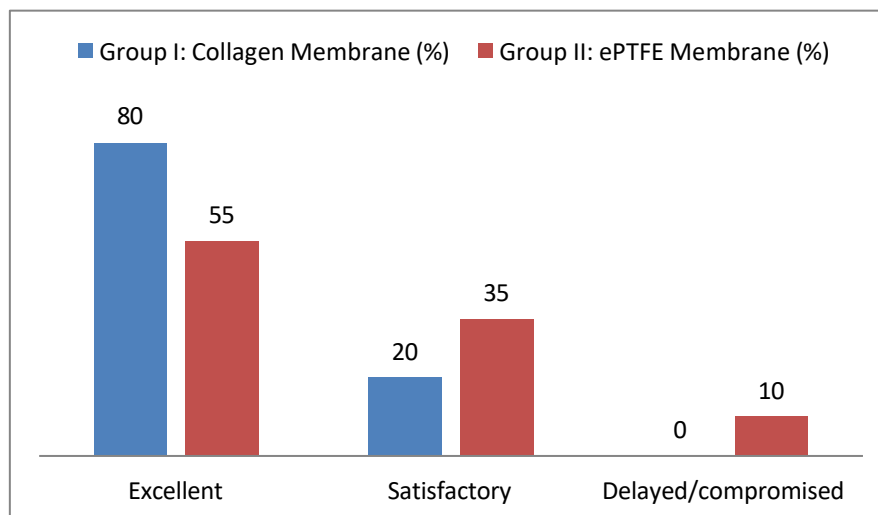


Figure 12: Intergruop Comparison of Soft Tissue Healing Outcomes in the Collagen Membrane and ePTFE Membrane Groups

Table 12 & Figure 13 present the comparison of membrane exposure between the two study groups revealed a greater incidence of membrane exposure in Group II (ePTFE Membrane) than in Group I (Collagen Membrane).

In the Collagen Membrane group, membrane exposure occurred in 1 participant (5.0%), while 19 participants (95.0%) showed no evidence of membrane exposure. In the ePTFE Membrane group, membrane exposure was observed in 5 participants (25.0%), whereas 15 participants (75.0%) had no membrane exposure.

Overall, membrane exposure was recorded in 6 of the 40 participants (15.0%), while 34

participants (85.0%) experienced uneventful healing without membrane exposure. Although the frequency of membrane exposure was higher in the ePTFE Membrane group than in the Collagen Membrane group (25.0% vs. 5.0%), the difference was not statistically significant ($p = 0.182$).

These findings suggest a tendency toward a higher incidence of membrane exposure in the ePTFE Membrane group. However, as the difference did not reach statistical significance, no definitive association between membrane type and membrane exposure can be established based on the findings of the present study.

Table 12: Comparison of Membrane Exposure Between the Study Groups

Membrane exposure	Group I: Collagen Membrane n (%)	Group II: ePTFE Membrane n (%)	Total n (%)	P value
Present	1 (5.0)	5 (25.0)	6 (15.0)	0.182
Absent	19 (95.0)	15 (75.0)	34 (85.0)	
Total	20 (100.0)	20 (100.0)	40 (100.0)	

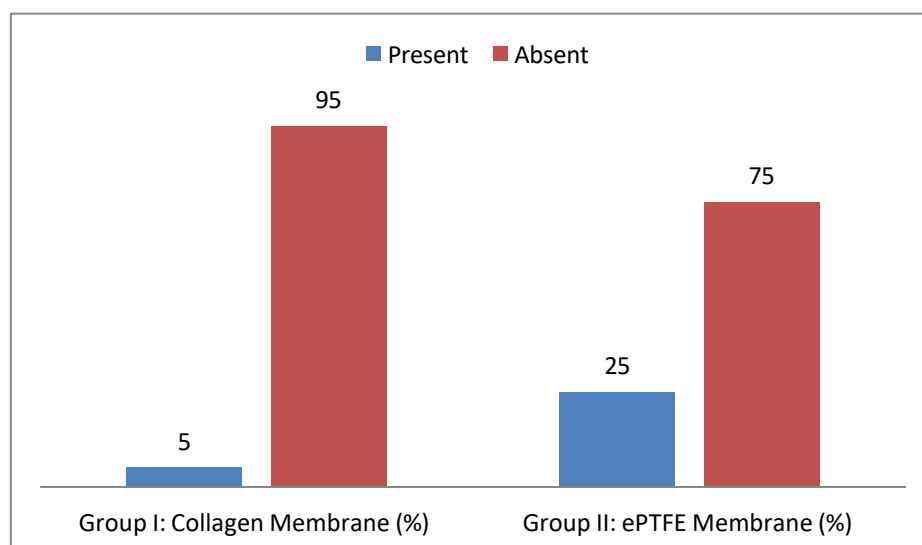


Figure 13: Intergroup Comparison of Membrane Exposure in the Collagen Membrane and ePTFE Membrane Groups

Table 13 & Figure 14 present the comparison of postoperative complications between the two study groups and show that the majority of participants in both groups experienced an uncomplicated postoperative course. However, postoperative complications were numerically more frequent in Group II (ePTFE Membrane) than in Group I (Collagen Membrane).

In the Collagen Membrane group, 17 participants (85.0%) experienced no postoperative complications. Membrane exposure, wound dehiscence, and postoperative infection were each observed in 1 participant (5.0%).

In the ePTFE Membrane group, 13 participants (65.0%) experienced no postoperative complications. Membrane exposure was the most common postoperative complication, occurring in 4 participants (20.0%), followed by

wound dehiscence in 2 participants (10.0%) and postoperative infection in 1 participant (5.0%).

The difference in the distribution of postoperative complications between the two study groups was not statistically significant ($p = 0.294$). Although the ePTFE Membrane group exhibited a numerically higher frequency of postoperative complications, particularly membrane exposure and wound dehiscence, the observed difference did not reach statistical significance.

Overall, these findings suggest that the Collagen Membrane group had a more favorable postoperative complication profile, with a greater proportion of participants remaining free of complications (85.0% vs. 65.0%). Nevertheless, both membrane types were statistically comparable with respect to the overall incidence of postoperative complications.

Table 13: Comparison of Postoperative Complications Between the Study Groups

Postoperative complication	Group I: Collagen Membrane n (%)	Group II: ePTFE Membrane n (%)	P value
No complication	17 (85.0)	13 (65.0)	0.294
Membrane exposure	1 (5.0)	4 (20.0)	
Wound dehiscence	1 (5.0)	2 (10.0)	
Postoperative infection	1 (5.0)	1 (5.0)	

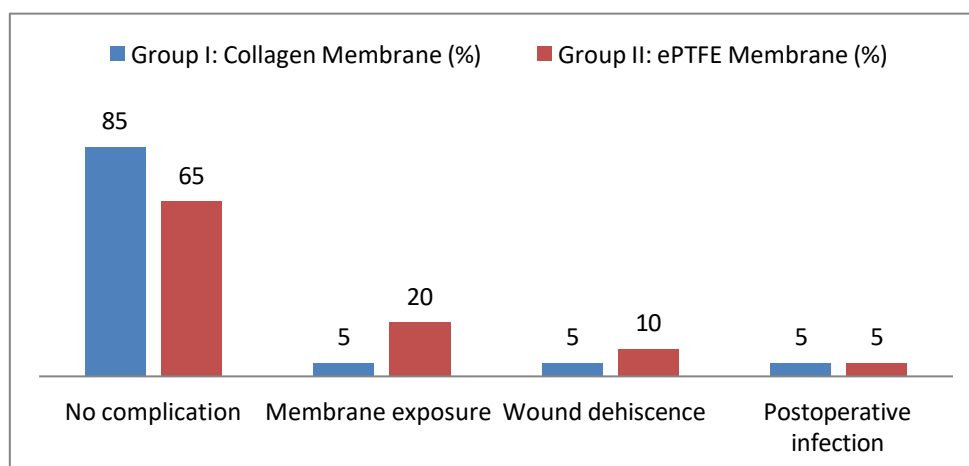


Figure 14: Intergroup Comparison of Postoperative Complications in the Collagen Membrane and ePTFE Membrane Groups

Table 14 & Figure 15 present the comparison of wound dehiscence between the two study groups. The findings indicate a higher numerical incidence of wound dehiscence in Group II (ePTFE Membrane) than in Group I (Collagen Membrane).

In the Collagen Membrane group, wound dehiscence occurred in 1 participant (5.0%), while 19 participants (95.0%) showed uneventful wound healing without dehiscence. In the ePTFE Membrane group, wound dehiscence was observed in 3 participants (15.0%), whereas 17 participants (85.0%) experienced no wound dehiscence.

Overall, wound dehiscence was recorded in 4 of the 40 participants (10.0%), while 36

participants (90.0%) remained free of this complication. Although the incidence of wound dehiscence was higher in the ePTFE Membrane group (15.0%) than in the Collagen Membrane group (5.0%), the difference was not statistically significant ($p = 0.605$).

These findings suggest that the incidence of wound dehiscence was comparable between the two membrane groups from a statistical perspective. Nevertheless, the lower frequency of wound dehiscence observed in the Collagen Membrane group indicates a favorable clinical trend toward improved soft tissue wound healing. However, this trend should be interpreted with caution, as the difference did not reach statistical significance in the present study.

Table 14: Comparison of Wound Dehiscence Between the Study Groups

Wound dehiscence	Group I: Collagen Membrane n (%)	Group II: ePTFE Membrane n (%)	Total n (%)	P value
Present	1 (5.0)	3 (15.0)	4 (10.0)	0.605
Absent	19 (95.0)	17 (85.0)	36 (90.0)	
Total	20 (100.0)	20 (100.0)	40 (100.0)	

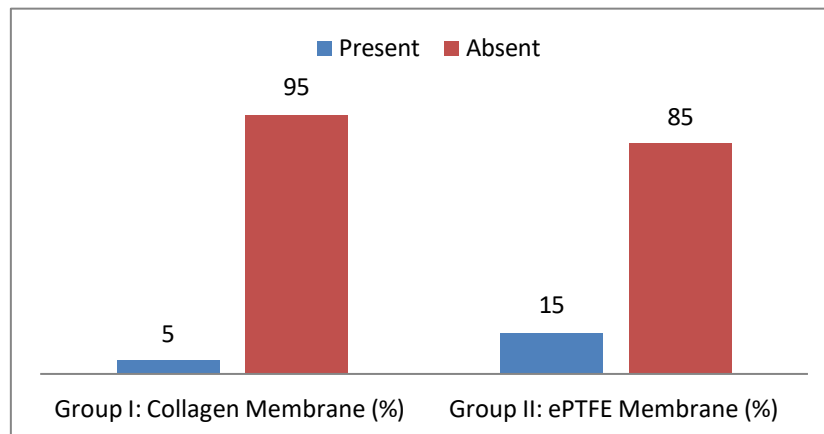


Figure 15: Intergroup Comparison of Wound Dehiscence in the Collagen Membrane and ePTFE Membrane Groups

Table 15 & Figure 16 present the comparison of postoperative infection between the two study groups. The findings indicate a low incidence of postoperative infection in both Group I (Collagen Membrane) and Group II (ePTFE Membrane).

In the Collagen Membrane group, postoperative infection was observed in 1 participant (5.0%), while 19 participants (95.0%) remained free of infection. In the ePTFE Membrane group, postoperative infection occurred in 2 participants (10.0%), whereas 18 participants (90.0%) experienced an uncomplicated postoperative course without infection.

Overall, postoperative infection was reported in 3 of the 40 participants (7.5%), while the

remaining 37 participants (92.5%) showed no evidence of infection during the follow-up period.

Although the incidence of postoperative infection was numerically higher in the ePTFE Membrane group (10.0%) than in the Collagen Membrane group (5.0%), the difference was not statistically significant ($p = 1.000$).

These findings suggest that both membrane types were associated with similarly low rates of postoperative infection. While the Collagen Membrane group demonstrated a lower numerical incidence of infection, the difference between the two groups was not statistically significant, indicating comparable postoperative infection outcomes.

Table 15: Comparison of Postoperative Infection Between the Study Groups

Postoperative infection	Group I: Collagen Membrane n (%)	Group II: ePTFE Membrane n (%)	Total n (%)	P value
Present	1 (5.0)	2 (10.0)	3 (7.5)	1.000
Absent	19 (95.0)	18 (90.0)	37 (92.5)	
Total	20 (100.0)	20 (100.0)	40 (100.0)	

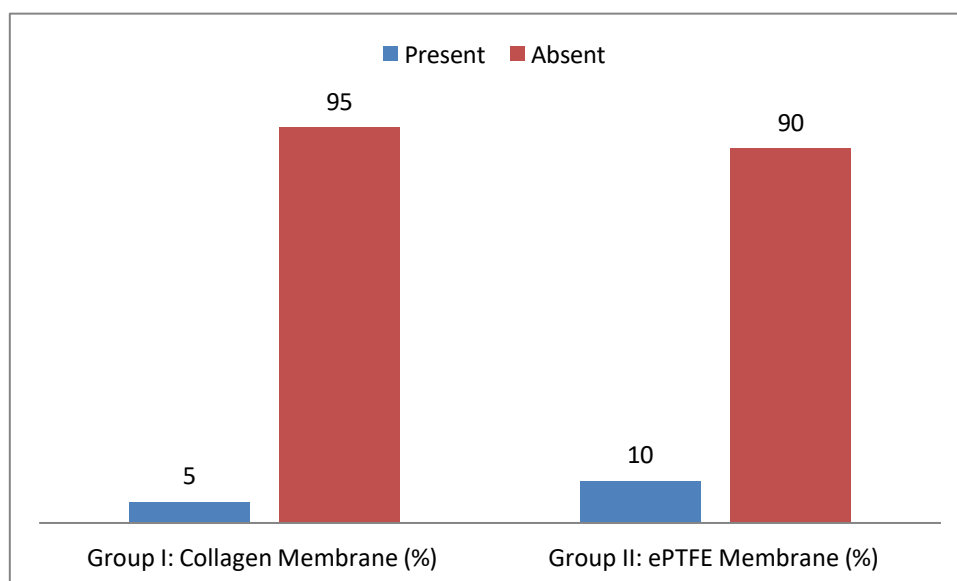


Figure 16: Intergroup Comparison of Postoperative Infection in the Collagen Membrane and ePTFE

Table 16 & Figure 17 present the comparison of implant survival between the two study groups at the 12-month follow-up. The findings demonstrate excellent implant survival rates in both Group I (Collagen Membrane) and Group II (ePTFE Membrane).

In the Collagen Membrane group, all 20 implants (100.0%) remained functional throughout the 12-month follow-up period, with no implant failures recorded. In the ePTFE Membrane group, 19 implants (95.0%) survived successfully, while 1 implant (5.0%) failed during the follow-up period.

Overall, 39 of the 40 implants (97.5%) survived successfully, with only 1 implant (2.5%) failing

during the study period. Although the implant survival rate was numerically higher in the Collagen Membrane group (100.0%) than in the ePTFE Membrane group (95.0%), the difference was not statistically significant ($p = 1.000$).

These findings indicate that both Collagen Membrane and ePTFE Membrane treatments achieved high implant survival rates over the 12-month follow-up period. While complete implant survival was observed in the Collagen Membrane group, the single implant failure in the ePTFE Membrane group did not result in a statistically significant difference between the two groups.

Table 16: Comparison of Implant Survival Between the Study Groups at 12 Months

Implant outcome	Group I: Collagen Membrane n (%)	Group II: ePTFE Membrane n (%)	Total n (%)	P value
Survived	20 (100.0)	19 (95.0)	39 (97.5)	1.000
Failed	0 (0.0)	1 (5.0)	1 (2.5)	
Total	20 (100.0)	20 (100.0)	40 (100.0)	

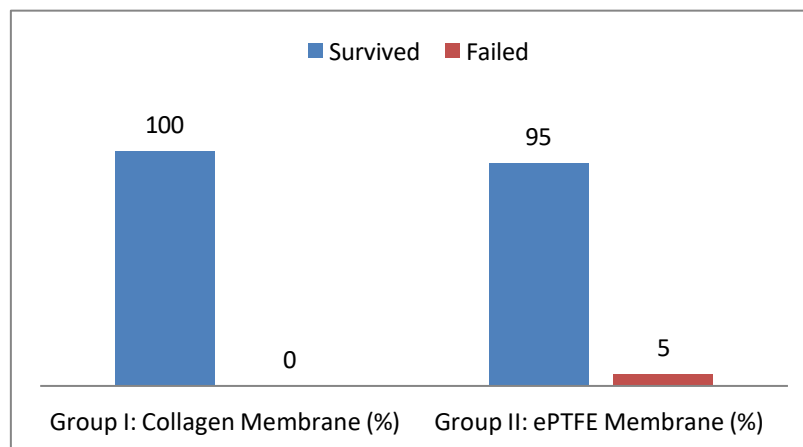


Figure 17: Intergroup Comparison of Implant Survival at 12 Months in the Collagen Membrane and ePTFE Membrane Groups

Discussion

The present study compared the clinical and radiographic effectiveness of resorbable collagen membranes and non-resorbable ePTFE membranes used during GBR around dental implants. Both membrane types successfully facilitated bone regeneration and supported implant placement; however, differences were observed in bone gain, implant stability, and complication rates. These findings are consistent with previous evidence indicating that membrane characteristics significantly influence the regenerative outcome of GBR procedures.

Sanz et al. (2019) [11] emphasized that successful bone regeneration in the craniofacial region depends on a combination of appropriate biomaterials, defect morphology, surgical technique, and maintenance of a stable regenerative environment. The authors concluded that barrier membranes remain an essential component of GBR by preventing soft tissue invasion and allowing selective repopulation of osteogenic cells. The favorable regenerative outcomes observed in the present study support these biological principles and reinforce the importance of membrane selection according to clinical indications.

The systematic review and meta-analysis by Thoma et al. (2019) [12] demonstrated that lateral bone augmentation performed simultaneously with implant placement is a predictable procedure with high implant survival and significant horizontal bone gain when

appropriate barrier membranes are used. Their findings showed that successful GBR can provide sufficient bone volume for long-term implant stability regardless of the membrane type, provided that adequate space maintenance and wound stability are achieved. Similarly, the present study demonstrated satisfactory implant stability and radiographic bone regeneration in both groups, although the ePTFE membrane group exhibited greater bone gain.

Experimental evidence provided by Schwarz et al. (2007) [13] demonstrated that effective space maintenance during GBR is a critical determinant of new bone formation. Their immunohistochemical investigation reported enhanced bone regeneration when stable barrier membranes were combined with suitable graft materials, highlighting the importance of maintaining the regenerative compartment throughout healing. The superior horizontal and vertical bone gain observed with ePTFE membranes in the present study may therefore be attributed to their greater mechanical rigidity and prolonged maintenance of regenerative space.

The systematic review conducted by Clementini et al. (2012) [14] reported high survival rates for implants placed in regenerated bone following both horizontal and vertical GBR procedures. Although regenerated sites may demonstrate slightly greater marginal bone remodeling than native bone, overall implant survival remains highly predictable. These observations

correspond with the present findings, where implants placed following GBR achieved favorable primary stability and successful osseointegration regardless of membrane type, with only minor peri-implant marginal bone changes during follow-up.

Sculean et al. (2008) [15] reviewed the biological basis of combining barrier membranes with bone graft materials and concluded that membrane-assisted regeneration promotes selective cell repopulation while maintaining clot stability and protecting the grafted area. The authors further emphasized that successful outcomes depend on membrane biocompatibility, wound stability, and adequate vascularization. These biological mechanisms explain the satisfactory healing observed in both study groups and support the use of GBR as a predictable regenerative procedure around dental implants.

The comprehensive review by Sheikh et al. (2015) [16] highlighted that successful alveolar bone augmentation requires biomaterials capable of maintaining structural integrity throughout healing while supporting angiogenesis and osteogenesis. The authors noted that non-resorbable membranes generally provide superior space maintenance in large or complex defects but require a second-stage surgical procedure for removal and are associated with a greater risk of membrane exposure. Conversely, collagen membranes offer superior tissue integration and reduced patient morbidity but possess lower mechanical stability. These conclusions closely align with the findings of the present study, in which ePTFE membranes demonstrated greater bone augmentation but a relatively higher incidence of postoperative complications, whereas collagen membranes exhibited favorable soft tissue healing and fewer complications.

Overall, the findings of the present study are in agreement with contemporary evidence supporting the effectiveness of both collagen and ePTFE membranes for GBR. While non-resorbable ePTFE membranes may provide superior regenerative space maintenance and

greater bone gain in challenging defects, resorbable collagen membranes offer excellent biocompatibility, simplified postoperative management, and reduced patient morbidity. Therefore, membrane selection should be individualized based on defect morphology, regenerative requirements, surgical complexity, and patient-specific considerations to achieve predictable implant-supported rehabilitation.

Limitations

The present study has several limitations that should be considered while interpreting the findings. First, the study was conducted at a single tertiary care center with a relatively small sample size, which may limit the generalizability of the results to larger and more diverse populations. Second, the follow-up period was limited to 12 months, precluding assessment of the long-term stability of regenerated bone, peri-implant tissue health, and long-term implant survival. Third, although all surgical procedures were performed using a standardized protocol by a single experienced operator to minimize variability, differences in the morphology and severity of alveolar bone defects may have influenced the regenerative outcomes. Furthermore, the study evaluated only two barrier membrane types—resorbable collagen membranes and non-resorbable ePTFE membranes. Therefore, the findings cannot be generalized to other membrane materials, including reinforced, titanium-reinforced, bioactive, or next-generation resorbable membranes. In addition, bone regeneration was assessed using clinical parameters and CBCT - based radiographic measurements; histological evaluation of the regenerated bone was not performed. Future multicenter randomized controlled trials with larger sample sizes, longer follow-up periods, and histological assessment are recommended to confirm these findings and provide stronger evidence regarding the long-term effectiveness of different barrier membranes for GBR around dental implants.

Conclusion

Within the limitations of the present study, both Both resorbable collagen membranes and non-

resorbable ePTFE membranes were effective for GBR around dental implants, providing predictable bone regeneration, high implant survival, and favorable clinical outcomes. The ePTFE membrane achieved significantly greater horizontal and vertical bone gain, whereas the collagen membrane demonstrated superior soft tissue healing with fewer membrane-related complications. Implant stability, peri-implant marginal bone preservation, and implant survival were comparable between the two groups. Therefore, membrane selection should

be based on defect characteristics, regenerative requirements, and patient-specific factors. Further multicenter studies with larger sample sizes and longer follow-up are needed to validate these findings. Further well-designed multicenter clinical trials with larger sample sizes and longer follow-up are required to establish evidence-based recommendations for membrane selection and to evaluate the long-term stability of regenerated bone and implant-supported restorations.

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