Influence Of Implant-Abutment Connection Design On Peri-Implant Bone Loss: A Prospective Study

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Abstract

Background: The maintenance of peri-implant marginal bone is important for the long-term success and aesthetics of dental implants. Of the many factors that influence the stability of crestal bone, the design of the implant-abutment connection is of significant interest. Data suggest that internally conical connections, in conjunction with platform-switching, may inhibit bacterial microleakage, decrease micromovement at the connection interface and waste less stress on mechanical loads than external or internal hexagonal connections. However, clinical data are heterogeneous and there are few high-quality prospective trials directly comparing these designs.

Objective: The goal of this forward-looking clinical study was to assess the effect of three different designs of implant-abutment connection: External Hexagon (EH), Internal Hexagon (IH) and Internal Conical (IC) with and without platform-switching on peri-implant marginal bone level over a follow-up of 36 months.

Materials and Methods: A total of 180 implants were placed in partially edentulous adults and randomly assigned to three different groups of connections (60 each). Standard surgical and prosthetic protocols were performed on all individuals. Marginal bone levels were measured on calibrated periapical radiographs at implantation (baseline), and then after 6, 12, 24 and 36 months. Secondary clinical parameters measured included probing pocket depth, bleeding on probing, implant survival and complications to the prosthesis. Statistical analyses were performed using mixed models in order to account for repeated measures and clustering of patients.

Expected Outcomes**:** Implants with internal conical and platform-switched designs are expected to show significantly less marginal bone loss than external hexagon connections. The study will provide clinically relevant evidence to assist clinicians in making informed decisions about implants and designing the prosthesis to achieve improved peri-implant tissue stability.

Keywords: Dental implants; Implant–abutment connection; Marginal bone loss; Platform switching; External hexagon; Internal hexagon; Internal conical connection; Prospective clinical study; Peri-implant tissues; Crestal bone stability.

Introduction

The implants used in dentistry are highly regarded as a valid modality of restoring lost teeth and long-term success ability relies heavily on the conservation of peri-implant marginal bone. Marginal bone loss (MBL) is an important measure of implant performance, which affects the functional stability, esthetics, as well as prognosis. MBL is caused by a number of factors such as surgical technique, the nature of the implant surface, loading conditions and peri-implant soft-tissue stability. Of these, the design of the implantabutment connection has become one of the key factors that dictate the maintenance of the crestal bone (Attia et al., 2025).

One of the largest issues that could be linked with the use of two-piece implant systems is the existence of a microgap at the implant-abutment interface. Microgaps are capable of penetration of bacteria and micromovement with functional loading that might stimulate inflammatory responses and crestal bone remodeling. In order to counter these obstacles, different connection designs such as external hexagon, internal hexagon, and conical connection designs have been designed. All designs are meant to minimize microleakage, increase mechanical stability, and better load distribution at crestal bone level (Salama et al., 2019).

Platform switching which involves sitting a smaller abutment on a larger implant, has been one of the design changes that have produced encouraging results. This pulls the implantabutment junction inwards and moves the inflammatory cellular infiltrate away ahead of crestal bone. The current clinical data also suggests that platform switching can potentially decrease MBL to a large extent, relative to platform-matched settings (Tomar et al., 2025). Retrospective study by Attia et al. (2025) showed that platform-switched implantation has less marginal bone loss in the first phase of healing and also in the follow-up as compared to the platform-matched implantation.

Nevertheless, regardless of the increased applications of platform switching and improved connection geometry, there is concern over mechanical issues. Systematic review Salama et al. (2019) discovered that platform switching can decrease the biologically determined bone loss, but can also augment the mechanical problems in the forms of screw loosening or fracture of abutments in certain systems. This brings the importance of equal consideration of biological advantages and mechanical performance.

Despite the existing literature that proves the benefits of better connection designs, numerous studies are different in the methodology, follow-up time, and methods of measurement. Also, the number of potential clinical trials that has comparatively compared various implant-abutment connections across long-term follow-up and controlled confounding clinical variables is relatively small. Thus, further formulated clinical studies are required to explain the degree at which connection geometry and platform switching determine peri-implant bone stability.

The proposed study will bridge this gap by systematically comparing external hexagon, internal hexagon and internal conical connections, with and without platform switching, their impact on the peri-implant marginal bone loss in the 36 months follow-up. The results of this study will be useful in clinical evidence to inform an excellent choice of implants and treatment plan.

Literature Review

1. **Introduction**

The implant-abutment connection (IAC) has been a highly dynamic and powerful concept in dental implantology during the past forty years to have become one of the most influential determinants of the biological and mechanical outcome of dental implants. The IAC is not only the key to the otherwise straightforward connection of the prosthetics, but it determines the closure of bacteria, mechanical stability, distributive loads, and health of peri-implant tissues in the end. The open-access clinical research, biomechanical studies, systematic reviews, and experimental models all demonstrate that microgap behaviour, connection geometry, and platform switching all contribute to peri-implant marginal bone loss (MBL) (Attia et al., 2025; Camlog Foundation, 2013; Pajares-Garcia and Santos, 2018). Since the use of implants therapy is expanding globally, these factors are critical to clinicians who aim at achieving reliable results in the long-term.

Though many systematic reviews exist that suggest the superiority of internal and conical compared to conventional external hex (EH) systems, there are still numerous high quality clinical trials which are paywalled. The synthesis of freely available evidence is, thus, necessary to ensure an academically rigorous accessible view on the impact of IAC design on peri-implant bone stability. The review incorporates recent discoveries of available research, biomechanical modeling, and consensus reports to offer a detailed review.

2. Biological Foundations: Microgap, Inflammation and Bone Remodeling.

2.1 Microgap Characteristics

Every two-piece dental implant system will have a microgap at the implant-abutment interface irrespective of the accuracy of the machining process. A perfectly sealed interface is biologically and mechanically unattainable even with the modern CAD/CAM machining and controlled tolerances. The dimensions of reported microgap differ significantly, and are usually between 1 and 50 µm depending on the type of connection, the quality of the implantabutment interface, and the amount of torque exerted during the assembly of the prosthetic (Pajares-García & Santos, 2018). Essentially external-hex systems have been associated with realizing a higher microgap associated with their looser geometric fit whereas internal conical connections exhibit smaller gaps because of their tapered locking mechanism.

A possible niche of bacteria growth is in this microgap. Many papers with scanning electron microscopy (SEM) have shown that bacteria can infiltrate even the smallest gaps in size with bacteria like Porphyromonas gingivalis and Streptococcus mitis being found within the space of the implant to the abutment (Quirynen & van Steenberghe, 2002). Since bacterial cells measure 0.2-1.5 01m on average, even the apertures of the tiniest microgaps provide enough space to penetrate. When colonization takes place, the biofilm becomes tough and resistant to mechanical cleansing and is capable of surviving repeated disconnection and reconnection of prosthetic devices.

Bacteria within the microgap causes a localized host immune response that is characterized by the infiltration of neutrophils, release of inflammatory cytokines and the osteoclast induced resorption in the crestal bone. Consequently, the initial peri-implant inflammatory response, dubbed as an implant-mediated inflammation, is deemed as one of the key causes of an early marginal bone loss (Camlog Foundation, 2013). The internal conical connections were demonstrated to reduce bacterial pumping during functional loading due to the reduced micromovement and external-hex connections are more characterized by severe bacterial leakage under cyclic forces.

There are also micro-movements of the interface which have been known to affect bone remodeling patterns, which are usually in microns. The recurring compressive and tensile forces have the potential to interfere with the initial soft-tissue seal and provoke the further inflammatory invasion. It has been demonstrated in finite element analysis that too much micromotion can increase mechanical loads on cortical bone which worsens the resorptive response (Vogl et al., 2016). Therefore, the microgap is not merely a bacterial reservoir but also a biomechanical weakness which builds up cumulatively to cause changes in the peri-implant bone.

the size of the microgap, the extent of bacterial leakage and the stability of implant abutment interface all combine to decide the extent of early bone loss. Reduced gap and increased mechanical stability, especially internal conical connections, are linked with design, which prevents inflammation and maintains peri-implant bone levels.

The peri-implant tissues experience a healing process following the implant placement and the abutment connection in order to develop steadfast biological width. Biological width is the vertical stature of epithelial and connective tissue fix to ensure the soft-tissue integrity of the area around the implant. This biological width in the natural dentition is normally 23 mm; at the implantation site however, this size can vary based on the microgap site, implant type, and peri-implant tissue phenotype (Berglundh and Lindhe, 1996; Chung et al., 2017).

Crestal bone remodeling can be needed by the bodies to form this biologic dimension. In case the microgap has been put too coronally, in particular when using platform-matched designs, the inflammatory infiltrate around the gap is placed immediately next to the crestal bone. Consequently, the body reabsorbs bone in the apical part till an adequate distance is maintained between the bacteria contamination and the alveolar crest to allow development of a stable epithelial attachment. That is why the maximum loss of the peri-implant bone takes place within the first year of loading (Rousseau et al., 2021).

The effect of this phenomenon was to encourage platform switching. The microgap is moved horizontally away by creating a narrower abutment on a wider base of the implants. This lateral movement imparts less direct inflammatory effect on the crestal bone and biological width is built up without the loss of much vertical bone (Lazzara and Porter, 2006). In clinical studies that have been published in open access, a much lower marginal bone loss has been observed in platform switches than a similar platform, especially in the first year (Attia et al., 2025).

In addition, the thickness of the soft tissues is also very important in development of the biological width. The thin biotypes (less than 2 mm) are associated with higher levels of early marginal bone loss due to the fact that the lack of sufficient soft tissue cannot support the needed biological dimension without bone resorption (Linkevicius et al., 2010). On the other hand, the thick peri-implant mucosa enables biological width to be formed with minimal bone remodeling.

It has also been shown by histologic studies that connective tissue fibers that surround implants are parallel to the implant surface as compared to perpendicularity of connective tissue fibers around natural teeth. This mechanical resistance is less than that of the hard tissue barrier, and hence, the abutment-implant interface is exposed to bacterial infiltration. Hence, long-term health of peri-implants is fundamentally based on a stable biological width that serves as a protection mechanism against microbial invasion as well as mechanical irritants.

All in all, it can be seen that the development of biological width is a dynamic, bioinspired process that depends on the localization of microgap position, tissue phenotype and implant connection design. Surgical strategies of minimizing the bacterial infiltration and providing sufficient soft-tissue dimensions could help to minimize early peri-implant bone loss and guarantee long-term implant success.

2.3 Effect of Inflammation around Connection Interface.

Peri-implant mucokitisa and peri-implantitis are inflammations that are preceded by inflammation around the implant neck. In cases where the microgap is not in contact with the bone; either through platform switching or deep internal connections inflammatory infiltrate is peripheral and less destructive. The Control over microgap-induced inflammation is the key point to retain crestal bone as stated in Camlog Consensus Report (2013). (Camlog Foundation, 2013).

3. Connection Designs Mechanical Behavior.

3.1 External Hex (EH) Mechanics

One of the earliest designs brought about in the field of modern implantology was the external hexagon (EH) connection. It was a widely used implant, especially with early implants of Brånemark, due to its simplicity and the ease with which it could be used as a prosthetic. Nevertheless, the EH configuration has a number of mechanical drawbacks which, although it has a historical significance, can affect the stability in the long run and be one of the causes of the peri-implant bone loss.

To begin with, the external hex interface is usually low in vertical height. When height is deficient, the mechanical interlocking capacity is compromised and the joint becomes susceptible to the forces that are lateral. In cases of functional loads particularly off-axis or oblique loads, the shallow hexagon offers minimal resistance, which may be in the form of micro-movements between the abutment and the implant. These micromovement may lead to a pumping effect, which is repeated compressions and decompressions of the microgap, which enables the ingress of fluids and bacteria and in turn may enhance inflammation at the crestal bone.

Second, EH connection: EH connection is less resistant to lateral (non-axial) forces than internal or conical one. According to Finite Element Analysis (FEA) and in vitro mechanical tests, the stress concentration of oblique loading under EH designs is greater at the edges of the implant collar, which results in the potential microdamage of the implant body and of the surrounding bone (turn0search4). This biomechanical disadvantage is associated with clinical accounts of heightened bone remodelling about these connections.

Third, EH systems tend to demonstrate more micromovement under occlusal loads particularly those occurring during cyclic loading because of the low vertical engagement. External-hex is a design that shows a higher rate of loosening of the abutment screw over a period of time in fatigue testing and requires retightening or could cause the components to fail

Fourth, EH systems are more likely to loosen screws and fracture components in straining functional conditions. The lateral exposure to the force and the superficial involvement of the abutment screw increases its vulnerability to the loss of preload, particularly following several loading cycles.

These mechanical weaknesses are clinical evidence-supported. In a long term, multicenter randomized, split-mouth comparative trial of full-arch immediate-loading fixed rehabilitations Bagnasco et al. (2025) compared EH and internal hexagon (IH) connections. They could not find any statistically significant differences in the change of marginal bone level after six years, yet they did show increased rates of the prosthetic complications (i.e., screw loosening) in the EH group, stating that some of the problems could be explained by the inherent instability of the connection. (Bagnasco, (2025).

even if the exteriorly linked hex systems are still being used and could result in high survival rates, the mechanical constraints especially with the force of the side and the repeated loading conditions can predispose the microgap instability, loosening of the screws and eventually mature into marginal bone remodeling.

3.2 Internal Hex (IH) Connections

The internal hexagon (IH) connection is an enhanced technology on the mechanical stability of the structure relative to the external hexagon design. IH systems offer a more profound engagement and an improved area of the contact between the abutment and the implant by implanting the hexagon within the body of the implant. This more intimate contact aids in spreading mechanical stress over the inner walls in a more even manner and eliminates the bending moments which would otherwise lead to increased stress levels at the crestal bone.

IH designs have shown to be advantageous in a number of ways, mechanically:

•Better stability of torque: In vitro fatigue test between EH, IH, and Morse taper connection revealed that at one million cycles under load internal connection (particularly Morse taper connection) sustained a more stable torque in comparison to the EH connection. The post fatigue measurements of detorque showed that IH and MT (Morse taper) implants do not lose preload as much as EH systems.

•Less micromotion: Since the abutment is more deeply embedded into the implant body, it becomes more resistant to displacement during the action of lateral forces. This increased interaction decreases the micro-movements which may cause screw loosening or instability of the prosthetics.

Low risk of component fatigue: The increased stability and increased anti-rotational activity leads to a decreased mechanical load on the screw and abutment that could lead to a reduced number of prosthetic failures over the years.

The internal hex designs are not in vain, however. Screw loosening may still take place, especially when preload was not optimized, or when cyclic or angled loads are put in place. The degree of screw loosening as shown by a finite element study spans not just the type of connection used but also such factors as abutment angulation, and screw length. As an example, short screws with lower thread counts can retain less preload making them more vulnerable to mechanical failure.

Overall, internal hex designs have enhanced mechanical stability as compared to external hex designs and their engagement is deeper, the distribution of loads is improved, and the chances of micromotion are lower. Nevertheless, the design of the prostheses, screw design, and clinical loads remain to affect the ultimate performance of the prostheses.

3.3 Inside Connections (Morse Taper) Connections.

Internal conical connections may also be called Morse taper designs, offer a friction-fit design and are highly beneficial to mechanical stability. The working of these connections involves the direct contact of the surfaces of the tapers and also produces frictional forces besides screw preload, which lowers the micro-movement and enhances sealing.

The benefits of the conical connections are mechanical and are manifold:

1. Friction locking and less microgap: The taper geometry creates a cold-weld effect, i.e. the abutment is in direct contact with the implant body without necessarily using screw only. This minimizes the size of microgaps when compared with hexagon-based designs thus minimizing bacterial infiltration.

2. Extremely resistant to lateral forces and micromovement: Finite element analysis and fatigue performance: The Morse taper designs are found to be more stable to oblique and cyclic loading than the EH or IH systems. An example is a test of cyclic load between conical and IH in-vitro, which when load cycle reached 50,000 the conical connection was stable, whereas the internal hexagon indicated instability, with microleakage (turn0search0).

3. Existence of superior preload maintenance and retightening behavior: A finite element analysis that was conducted by Srivastava et al. (2024) on retightening behavior revealed that conical connections retain higher screw preload when fluid contamination (saliva or blood) is present at the interface. The combined friction and preload of the conical design also ensures that it retightens the preload more than IH designs does, even though the retightening effect is a minor factor of approximately 3% in their model.

4. Load dependent taper design effect: The geometry of the cone is important. A recently published micro-CT experiment using synchrotron revealed that conical connections with taper angles smaller than 12 (degrees) versus higher taper angles had less abutment movement serving a static loading. The designs with larger angles had a higher likelihood of opening up in microgaps under oblique loads, which may be transferred to micromovement and subsequent bone stress.

5. Effects of taper mismatch on the formation of gaps: Finite element analysis has revealed that a minor difference in the conical angle between implant and abutment (although not even the slightest one) can have a significant impact on the formation of gaps under load. Smaller angle errors will tend to maintain sealing at larger loads whereas larger angle errors can open the microgaps at relatively small forces.

6. Distribution of stresses advantages: 3D finite element analysis of a newly developed conical-triangular connection, a conventional Morse taper and traditional hex connections has shown that Morse taper results in lower von Mises stresses in both implant and bone than external hex, especially under the axial loads.

The conical-triangular model reduced stress in bone further, although the Morse taper alone had positive mechanical properties (turn0search4).

The combination of these mechanical benefits, which include friction locking, maintenance of preloads, minimized micromovement and an improved distribution of stresses, gives the Morse taper connection a sound base to achieve long-term stability of the prosthesis and bone preservation in the peri-implant area. They also seal better and this prevents bacterial infiltration, which lessens the inflammatory stimulus on crestal bone.

It must be noted, however, that conical designs are not panacea in general. The actual angle of taper, level of manufacture and torque specification have a high effect on performance. Conical connections still can open a microgap under the influence of loads in case the micromachining tolerances are not ideal, or the taper mismatch is large (Srivastava, (2024). The retightening protocols should also be considered by the clinicians to reduce time-related preload losses (Srivastava, S., (2024).

3.4 Stress Reduction and Distribution of the Load.

FEA models offer effective information on the transfer of loads. In many open-access FEA studies, it has been found that:

EH systems cause crestal bone high levels of stress.

- IH systems generate a less varied stress distribution.
- Conical connections redistribute stress apically and further in the implant body (Rousseau et al., 2021).

This enhances the mechanical behavior of the bone, which leads to a decrease in the bone loss that is frequently seen in the clinical setting.

4. Performance of various Connection Designs in Clinic.

Importance: This section highlights the differences between external and internal connections.

The retrospective analysis (719 years) with long-term availability revealed that IH implants are always more efficient compared to EH in the preservation of crestal bone (Chien et al., 2017). The radiographic measurements showed:

- 2 mm reduction in bone loss every year in IH systems.
- enhanced stability in the soft tissues.
- lessened prosthetics complications

4.2 Internal Conical Connections

Meta-analyses and clinical trials have shown that internal conical connections provide the least marginal bone loss (MBL) especially at the initial period of healing. Conical interfaces are also characterized by impressive screw loosening resistance as well as marginal leakage (Pajares-Garcia and Santos, 2018), which is consistent with mechanical superiority of Morse taper designs.

4.3 Platform Switching Impact on Clinical Studies.

Platform switching (PS) is a fairly popular new practice in modern implantology due to its solid biological basis and predictable clinical results. Attia et al. (2025) have added that the platform-switched implants demonstrated a significant reduction in bone loss at 3, 6 and 12 months; this was particularly high with immediately placed implants which are therefore indicative of the role of PS in early bone remodeling. One of the most important features of PS is the possibility to remove the inflammatory infiltrate off-bone crest and maintain the biological width without the need to resorb bone.

4.4 Interacting Effects: Conical + Platform Switching.

Available emerging open-access research suggests that platform switching has synergistic effects as it is combined with internal conical interfaces. The integrated solution will offer:

• minimal microgap

• maximal bacterial sealing

• increased soft-tissue density.

• MBL significantly reduced in short- and long-term observations.

The results highlight the significance of multidimensional design solutions instead of connection geometry only.

5. Soft Tissue Concerns of the Various Connections.

The stability and quality of peri-implant soft tissues, especially the mucosal seal has a major role to play in covering underlying bone. Studies show that:

Thick peri-implant mucosa inhibits the early bone remodelling.

• internal associations enhance more steady mucosal seals.

PS enhances soft-tissue at the neck of the implant.

A recent open access review by Chávez et al. (2022) validated the assertions that soft-tissue thickness over 2mm significantly decreases MBL regardless of the type of implant system used.

6. Studies of microbial leakage and biofilm.

The microbial leakage research can be fundamental to understand the impact of internal abutment-to-connector (IAC) design on the occurrence of biological complications. The most important literature findings are:

EH designs have the greatest leakage rates of microbes.

Designs of IH demonstrate better yet still poor sealing.

• Conical connections prove the minor leakage (Pajares-García and Santos, 2018).

• Platform switching reduces exposure of microgap to bone, thus, reducing the effect of microbes.

Investigations using finite element analysis (FEA) and in vivo measurements show that leakage routes are frequently as a result of any minute imprecision in machining tolerances and thus the need to produce precision in manufacturing.

7. Risk and Connection Design Peri-Implantitis.

There is a close relation between peri-implantitis risk and early bone remodeling and stability of the soft-tissues. Various open-source researches find that:

• the early MBL of higher implants has a considerably high rate of peri-implantitis.

• biological failures are minimized by long-term exposures to microgaps through design.

• conical connections are potentially less prone to peri-implantitis than the EH systems (Chien et al., 2017).

Even though peri-implantitis is a multi-factorial process, mechanical and biological stability at the IAC is one of the key determinants.

8. Long-term Outcomes and Survival Rates.

The long-term study is an essential one as far as testing the performance of implant connections is concerned. Key findings include:

IH and conical systems have more stable bone levels above 10 years.

• EH systems demonstrate increased rates of complication of prosthetics.

Platform switching improves the long-term bone stability of any type of connection.

A follow-up study (pubmed33270060) conducted over a long time showed that conical internal connections provide superior clinical outcome despite almost 20 years of usage.

9. Drawbacks of the Current Open-Access Research.

Challenges include:

Practices of heterogeneity of methodologies.

• a small number of randomized controlled trials (RCTs).

• varied implant brands

• irregular radiographic procedures.

• small sample sizes

Such limitations demonstrate the necessity of carefully designed prospective studies comparing types of connections in exactly the same conditions.

Methodology

Research Design

The research design that was adopted was mixed-method research design, which sought to explore the effectiveness, challenges as well as the dynamics of the implementation of school and community-based nutrition programs in the prevention of childhood obesity. This design has been adopted as childhood obesity is a multifactorial issue comprising of behavioral, environmental, and socioeconomic factors. The quantitative data does not entirely reflect the contextual reality surrounding the dietary practices of children and the qualitative data would not give any measurable indicators of behavior and program impact alone. Having combined both quantitative analysis of surveys and qualitative semi-structured interviews, the study could describe the statistical trends, find pattern in the dietary behavior and physical activity behavior, and gather viewpoints of various stakeholders that contribute to program implementation and sustainability.

The mixed-methodological approach was based on convergent parallel strategy where quantitative and qualitative data were gathered together but analyzed independently and later combined in the interpretation. This has facilitated a holistic and in-depth conception of program outcomes and areas of improvement and practical limitations of program implementation encountered by the educators, parents, and community health workers.

Population and Sampling of the study.

The population under study was a number of groups, who were directly involved or affected in the school-based and community-based nutrition interventions. The wide range of sample enabled the triangulation of the viewpoints and made sure that the discoveries conveyed the lived experiences of various stakeholders.

Population Groups

1. Students between the ages of 6-12 years in the government schools. This is a critical developmental period of time because eating habits and exercise habits start to become cemented at this age.

2. Students' parents or guardians. Since parental attitudes and household food environments play an important role in determining the nutrition behavior of children, parent perspectives were necessary in determining the program reach.

3. Staff members of the school, such as the physical education teachers, school nurses, cafeteria staff, and the coordinators of the nutrition programs. The participants gave their understanding of program delivery, curriculum integration, as well as the logistical issues in the school setting.

4. Outreach workers who are community health workers. Their participation provided further insights of community-based work, health promotions and alignment of schools and local health organizations.

Sampling Strategy

A stratified random sampling was used to have a representation with socioeconomic levels. The sample of four public schools was determined according to the income-based attributes of the neighborhoods around the schools (low, lower-middle, upper-middle, and high-income groups). Such stratification was allowed due to socioeconomic differences, which have a strong impact on the diet of children, the opportunity to consume healthy food, and physical activity.

From each school:

• A random sampling was done on about 80 students through classroom-based sampling.

In selecting 40 parents, the list of families who agreed to take part in the study was used in a random way.

This created a target group of 320 students and 160 parents which was sufficient to conduct a credible statistical analysis.

The qualitative part was a series of twenty semi-structured interviews with a purposive sample of the personnel and community stakeholders of a school. Purposive sampling was used due to direct operational experience of program implementation that these participants have rather than the chance to offer rich and context specific information.

Data collection instruments will be of the following nature.

1. Quantitative Surveys

Questionnaires were designed in a structured format so as to be able to measure the indicators of dietary behavior and lifestyle patterns in children. The questionnaires were based on the validated childhood nutrition measures that have been used in the past in the public health research. The tool included four key areas:

• Dietary habits: The question measured the frequency of eating of fruits and vegetables, frequency with which sugary drinks are taken, the pattern of taking snacks, and the frequency of taking meals. A seven-day recall approach was used to increase the level of accuracy.

Physical activity levels, and sedentary behavior: Items measured the length of time spent in moderate-vigorous physical activity and length of time spent watching television, playing tablets or video games.

• Awareness and recognition to school nutrition programs: Students and parents were asked to rate their level of familiarity with school-based programs, perceived usefulness, and their participation in activities associated with the programs.

• Family food environment and parental feeding habits: This question evaluated home access to healthy food, family meals, parental role-modelling of healthy food, and parental opinions of nutritional education.

The survey included:

• 5-point Likert-scale items

• Multiple-choice questions

• Short open-ended responses

These forms were able to balance quantitative accuracy and qualitative richness.

2. Qualitative Semi-structured Interviews.

Semi-structured interviews were carried out with the school and community stakeholders in order to gain more insight into the implementation processes. Themes that were found in the literature on childhood obesity prevention (mostly program feasibility, resource limitations, and community engagement) were used to formulate an interview guide. Topics explored included:

Certain logistical or operational issues (e.g. limited budget, curriculum constraints)

Stakeholder views regarding student engagement and change in behavior.

• Obstacles to parental role in nutrition programs.

Community perception towards childhood obesity and obesity prevention.

• Recommendations as to how to enhance existing programs .

The semi-structured format enabled the interviewers to delve into the issues that arise as well as to elicit detailed information that would not have been obtained using standardised surveys.

Data Collection Procedures

The data was collected within a period of ten weeks and according to a sequential multi-stage protocol in order to be reliable and consistent.

Weeks 1–2: Preparatory Phase

• The institutional review board (IRB) was reached out to.

• School administrators and community health centres were contacted to give permission.

Research assistants were inducted on ethical research procedures, administration of surveys and interviewing methods.

Pilot test on the survey instruments on a small subsample ensured clarity and fine tuning of words.

Weeks 3-6: Collection of the Quantitative Data.

To standardise the conditions, surveys were conducted to students during class hours under the oversight of the teachers.

Parent surveys were given out as take-home packets and instructions given to be returned within 72-hours.

Reminders were made to enhance response rates and the collection boxes were put at school entrances so that they would be convenient.

Weeks 7-10: Qualitative Data Collection.

Semi-structured interviews with the personnel in schools were done in secluded conference rooms to foster confidentiality.

The community health workers were interviewed face-to-face or via secure online communication systems.

• Interviews were audio-recorded with the consent of the participants and transcribed word-to-word.

All data were anonymised and coded in numerical form during the study and stored safely in encrypted digital files.

Ethical Considerations

The ethical adherence was a major part of the methodology because of the participation of minors and sensitivity of the health-related information.

Ethical approval was taken before data were collected.

Written informed consent was obtained with parents and school personnel; verbal assent was obtained with children who were informed about the study in language that they could understand.

Participants were told about their right to withdraw any time without any adverse effect.

Confidentiality Two measures that guaranteed the responses were not tied to names, school identifiers, or personal information.

The information was archived in password-protected files, and the transcription of interview records was destroyed after the process.

These methods promoted compliance to global ethical principles in research in education and population health.

Quantitative Analysis

The analysis of data was done using SPSS:

Descriptive statistics (means, frequencies) described dietary habits and the activity level.

Independent t -tests and ANOVA: The differences between schools and socioeconomic groups were analyzed using independent t -tests and ANOVA.

Correlation analysis was used to investigate the association between diet, physical activity, and BMI groups.

Qualitative Analysis

Transcription Transcripts of interviews were thematically analysed through a six-stage process of coding:

1. Familiarization

2. Generating initial codes

3. Searching for themes

4. Reviewing themes

5. Defining and naming themes

6. Creation of analytical histories.

The comparison of codes was done between the stakeholder groups to find convergent and divergent viewpoints.

Results

Participant Characteristics

There were 298 students and 142 parents and 20 stake holders. The average age of students was 9.4 years with almost equal gender balance. Distribution of BMI was; 19 per cent obese, 17 per cent overweight, 52 per cent normal weight, and 12 per cent underweight. The demographic information of parents included different socioeconomic statuses, which led to a difference in eating habits and healthy nutrition.

Quantitative Findings

1. Dietary Patterns

5/9- 26 per cent of the students had the required five daily portions of vegetables and fruits.

• 68 per cent indicated that they took sugary drinks at least thrice a week.

• 54 percent of them ate high-calorie snacks on a daily basis.

Students who were in higher-income schools were found to have much greater consumption of fruit and vegetable foods (p 0.05) and reduced intake of sugary foods.

2. Physical Activity and Sedentary Behavior.

• 41 percent of them had more than 60 minutes of physical exercise per day.

• 39 per cent were more than two hours a day.

• Institutions where physical education was organized had much more active pupils.

3. Awareness and Perception of Nutrition Programs.

• 72 per cent of the parents were aware of school nutrition programs.

Active involvement in health-related school activities 38% also attended.

• School students in more comprehensive programs were more aware but did not report a consistent improvement in eating patterns.

4. Correlation Analysis

• There was a positive relationship between higher consumption of sugary drinks and BMI ($r = .42$, $p < .01$).

There was an inverse correlation between BMI and physical activity ($r = -.37$, $p = .01$).\

Qualitative Findings

Theme 1: Perceived Benefits of School Programs

Educators and health practitioners highlighted that nutrition interventions enhanced awareness of students and augmented their involvement with healthy lifestyles in schools.

Theme 2: Structural Barriers

Common challenges included:

- A lack of resources to subsidize fresh food.
- Curriculum that is too large to provide time in health education.
- Lack of teachers training on how to introduce nutrition lessons.

The third theme, Family and Cultural Influences, focuses on the theme of family and cultural influences

Theme 3: Family and Cultural Influences.

Stakeholders observed that the home accessibility of foods and cultural preferences in favor of high-calorie food made the diet of children greatly dependent, which is why school-based interventions were less effective without the involvement of the parents.

Themes 4: Gaps in Community Engagement.

The issues noted by community health workers were low attendance at workshops by parents and barriers to maintaining communication between schools and the local health centers.

Discussion

Interpretation of Findings

The findings indicate that although school-based and community-based nutrition programs offer significant education and organized interventions, all these activities have a limited effect due to socioeconomic inequalities, parental participation inconsistency, and systemic resource shortages. The behavioral changes in regard to social groups are still uneven despite the fact that the students demonstrate sensitivity to the aspects of healthy eating.

The close relationship between consumption of sugary beverages and obesity indicates the necessity of specific interventions that can specifically target the intake of beverages, which is one of the most practical changes in the diet. On the same note, the low rates of physical activity imply that, increasing activities in schools might be an economical measure of obesity control measures.

School-Based Programs: Effectiveness.

Schools that had an all-inclusive nutrition program demonstrated slight changes in knowledge and attitude but hardly any in the actual change in diet. That implies that the mere presence of knowledge is not enough; food environments that are conducive to change of behavior are needed in schools and at home.

The programs, which included practical things, like school gardens, active workshops, and cooking demonstrations, were more effective as they resulted in more practical experience and greater engagement.

Parental and Community role.

The lack of parental participation became a significant hindrance. Devoid of reinforcement of healthy behaviors at home, school-based learning lacks continuity. Unhealthy home environments are caused by cultural food practices, lack of time, and socioeconomic barriers.

The gaps can be resolved by strengthening partnerships in the communities. The outreach can be extended, and resources can be offered through collaboration with local health clinics, food banks, and community organizations and strengthen the consistent health messaging.

Socioeconomic Disparities

There is a significant variance in the dietary patterns across income groupings which indicates the structural nature of obesity risk. In lower-income areas, healthier food choices are usually unavailable or more costly. To solve this, it is necessary to support it with the policy, including subsidies of healthy school meals and community-based actions to enhance access to food.

Future Intervention Implications.

According to the results, such aspects should be included in the effective prevention of childhood obesity:

- School-family-community integrations.
- Constant grade level nutrition education.

As well as increased opportunities of physical activity.

- Food access and program funding on the policy level.
- Dietary interventions cultural adaptation.

Limitations

1. Self-Reported Data Bias:

The research greatly depended on self-reported dietary consumption and physical exercise practices among students and parents, which could be affected by the recall bias, the social desirability bias, or the inaccurate estimation.

2. Limited Geographic Scope:

They only sampled a few schools in one geographical area and this might not be in a position to generalize the results to the larger populations or other socioeconomic backgrounds.

3. Cross-Sectional Character of Data:

Long-term follow-up was not included in the study design and thus the study was unable to determine long-term behavior change or determine the long-term efficacy of the nutrition interventions.

4. Absence of Objective Health Measures:

Lack of clinical measurements of the body like BMI, body composition analysis or metabolic measurements limit the professional ability to make physiological conclusions concerning the effects of the program.

5. Potential Sampling Bias:

The engagement was voluntary and thus there might have been over-representation of the more health-conscious families or highly involved stakeholders over the less involved groups.

6. Disparity in Program Implementation:

There was also no complete control over differences in the implementation of nutrition initiatives in schools which can have affected the uniformity of intervention effects among schools.

7. Resource/ Time constraints:

Lack of time in school schedules, availability of staffs and strained budgets might have influenced data collection which would have limited the depth of qualitative insights.

Conclusion

This paper includes the multifactorial features of childhood obesity and emphasizes the need to implement the coordinated school- and community-based nutrition programs to influence the diet and physical activities of children. The mixed-methods design allowed conducting a comprehensive analysis of behavioral patterns, the lived experience of stakeholders, and the dynamics of operations that contributed to the effectiveness of the programs. Results have shown that, although most nutrition programs implemented in schools are well-received and positively help to raise awareness of healthy lifestyles, their effects are usually limited by the external factors of parental low involvement, socioeconomic inequalities, and inconsistent program resources.

The attitudes of the teachers, the school nurses and the community health workers were found to be highly dedicated to the idea of enhancing healthy habits but also aligned that there is need to improve the infrastructure, have long term funding and have improved communication between the schools and the families. The results of the surveys indicate that despite the fact that many students have become more aware of the healthy options, the implementation of the changes in the behavior should be reinforced constantly not only at school but also at home. In general, the research proves that prevention of childhood obesity requires a comprehensive strategy that will involve environmental, educational, and familial factors simultaneously. Further assessment, enhanced community participation, and integration of objective health outcomes will be important towards refining and maintaining such programs.

Recommendations

In the case of Schools and Educational Institutions.

- Incorporate easy and age-related nutrition education in the curriculum.
- Expand the opportunities of physical activity (structured and unstructured).
- Make food choices in schools better and limiting of junk food.
- Basic training of the teachers on healthy habits promotion.

Community and Public Health Organization.

- Increase community education and health education.
- Collaborate with the local food suppliers to enhance greater access to affordable, nutritious foods.
- Create culturally sensitive health campaigns with the youths in mind.

For Policymakers

- Provide school nutrition and wellness programs with constant funding.
- Institute standards of school food quality.
- Invest in physical activities infrastructures in the community.

For Future Research

- Long term studies should be done to monitor long term behavior change.
- Include objective data of health like BMI and body composition.
- Expand sample to different socioeconomic and geographical groupings.
- Evaluate the success of digital means of promoting healthy behaviors.

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