Evolution of Aesthetic Dentistry

Journal of Dental Research
2019, Vol. 98(12) 1294–1304

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DOI: 10.1177/0022034519875450
journals.sagepub.com/home/jdr

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Abstract

One of the main goals of dental treatment is to mimic teeth and design smiles in a most natural and aesthetic manner, based on the individual and specific needs of the patient. Possibilities to reach that goal have significantly improved over the last decade through new and specific treatment modalities, steadily enhanced and more aesthetic dental materials, and novel techniques and technologies. This article gives an overview of the evolution of aesthetic dentistry over the past 100 y from a historical point of view and highlights advances in the development of dental research and clinical interventions that have contributed the science and art of aesthetic dentistry. Among the most noteworthy advancements over the past decade are the establishment of universal aesthetic rules and guidelines based on the assessment of natural aesthetic parameters, anatomy, and physiognomy; the development of tooth whitening and advanced restorative as well as prosthetic materials and techniques, supported by the pioneering discovery of dental adhesion; the significant progress in orthodontics and periodontal as well as oral and maxillofacial surgery; and, most recently, the implementation of digital technologies in the 3-dimensional planning and realization of truly natural, individual, and aesthetic smiles. In the future, artificial intelligence and machine learning will likely lead to automation of aesthetic evaluation, smile design, and treatment-planning processes.

Keywords: cosmetic dentistry, maxillofacial surgery, orthodontic(s), prosthetic dentistry/prosthodontics, periodontal medicine, restorative dentistry

Introduction

Aesthetic dentistry is not a special discipline or area of dentistry by itself, but with functional and biological considerations, it represents one of the goals of dental treatment interventions, spanning all specialty areas, from preventive and restorative dentistry to prosthodontics, orthodontics, periodontics, as well as oral and maxillofacial surgery.

The quest to improve the appearance of the face and teeth dates back to ancient history (Peck and Peck 1970; Hoffmann-Axthelm 1981). In the 18th century, spurred by the pioneering work of the likes of Pierre Fauchard (1678–1761; Bolla et al. 2014), dentistry developed as a separate medical discipline, facilitating specialized treatment of functional and aesthetic dental deficiencies. While preventive measures, tooth replacement materials, and partial as well as complete denture fabrication techniques were constantly advanced afterward, it was the 20th century that saw the most significant breakthroughs in aesthetic dentistry. Figure 1 depicts a timeline of key discoveries in the field over the last century. Figure 2 presents an example of treatment of aesthetically compromised maxillary anterior teeth with current digital and adhesive technologies.

There is ample and strong scientific evidence that the appearance of a person's face (Root 1949; Peck and Peck 1970; Jacobs et al. 1971; Cellerino 2003; Rhodes 2006) and teeth (Anderson 1965; Newton et al. 2003) has a profound impact on the perception and judgment by others. Aesthetically pleasing teeth are associated with kindness, popularity, intelligence, and high social status (Shaw et al. 1985). Arguably even more important is the fact that the level of satisfaction with one's own smile attractiveness is directly correlated with self-perception and certain psychological traits (Arndt et al. 1986; Davis et al. 1998). An unattractive smile is correlated with the personality characteristics of neuroticism and self-esteem (Van der Geld et al. 2007), ultimately affecting overall well-being and health. Despite the large body of evidence on the importance of an attractive smile, the actual need for aesthetic or elective cosmetic dental treatment has always been discussed controversially due to ethical concerns (Gilbert 1988; Liebler et al. 2004) and the fact that improper, unnecessary, unsuccessful, overly invasive, and excessive treatment can have severe detrimental consequences on the attractiveness and well-being of the patient. One of the greatest challenges in this context is

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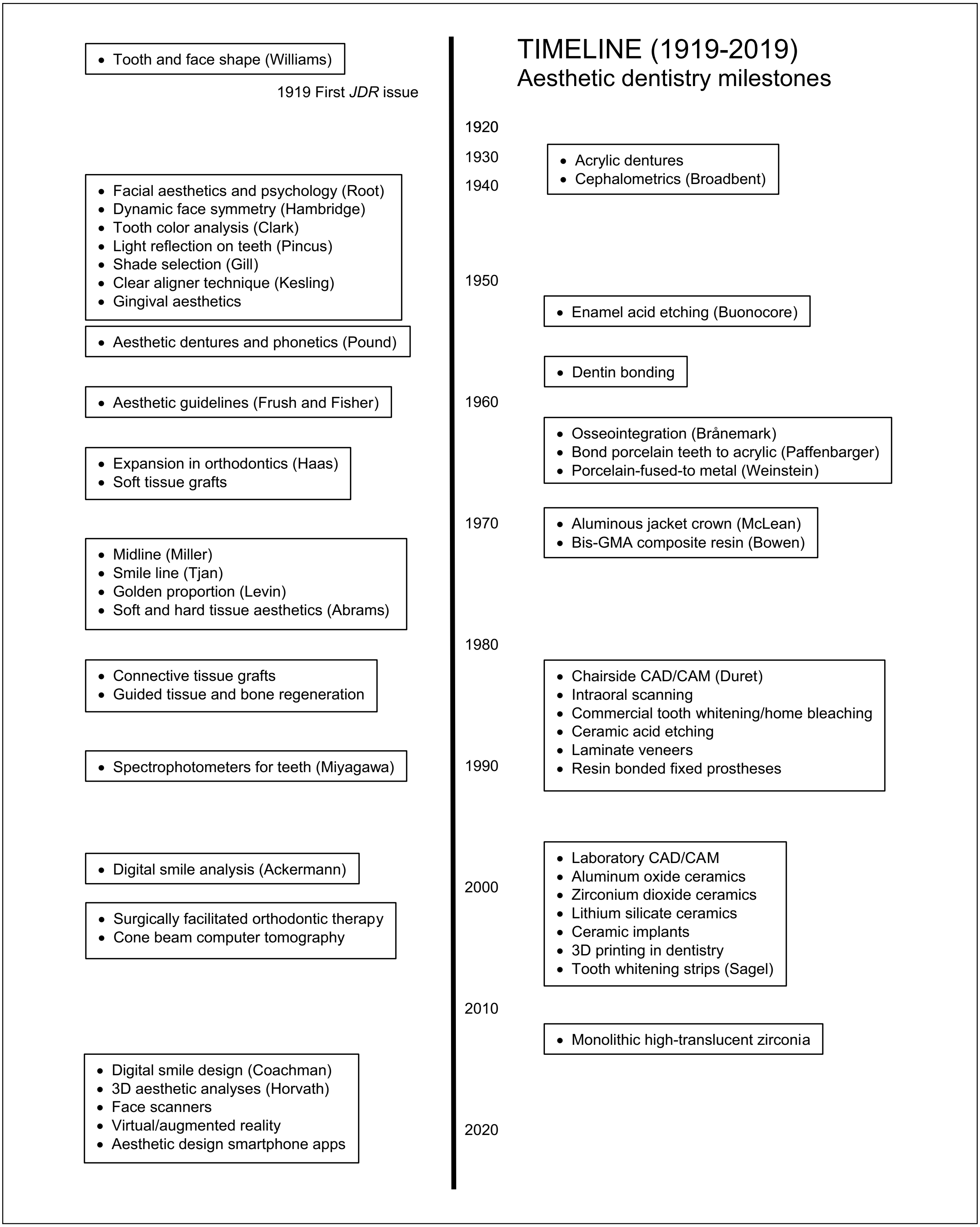

Figure 1. Timeline of milestones in aesthetic dentistry (1919 to 2019). Entries display, in chronological order, select significant developments and discoveries that occurred each decade. CAD, computer-aided design; CAM, computer-aided manufacturing.

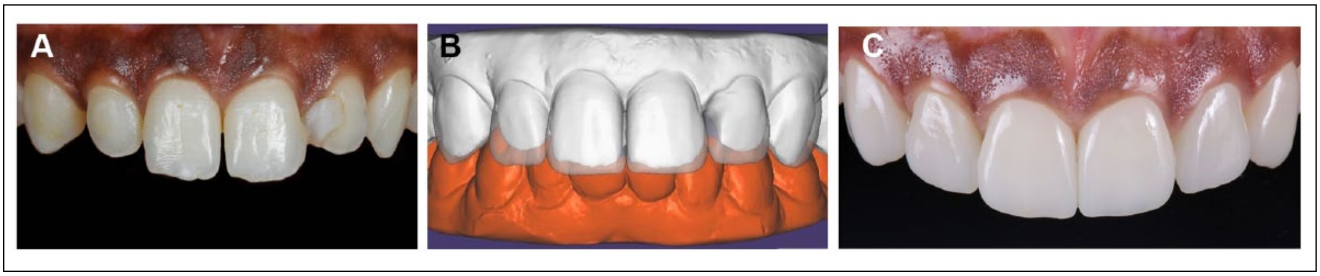

Figure 2. Rehabilitation of aesthetically compromised maxillary anterior teeth with current technologies. Preoperative intraoral situation (**A**). Natural tooth shapes from a digital tooth library were selected (**B**) to fabricate CAD/CAM laminate veneers. Postoperative situation (**C**). CAD, computer-aided design; CAM, computer-aided manufacturing.

that every person is different and so is his or her smile, aesthetic needs, and perception of harmony and beauty (Arndt et al. 1986; Ahmad 2005). Perception has a psychological basis, and a frequent discord between lay and professional opinions regarding dental aesthetics is well documented (Brisman 1980; Parrini et al. 2016). Consequently, the role of the clinician and dental technician in understanding and realizing the patient's aesthetic visions and needs has its challenges.

This article gives an overview of the evolution of aesthetic dentistry over the past 100 y from a historical point of view and highlights advances in the development of dental research and clinical interventions that have contributed to the science and art of aesthetic dentistry.

Aesthetic Guidelines

The understanding of natural tooth arrangements, positions, proportions, shapes, color, and morphologies (Hall 1887) is the foundation of aesthetic dentistry to mimic nature as closely as possible (Goldstein 1969). This understanding and associated parameters were assessed and manifested over decades by numerous authors, often based on subjective observations and perception rather than scientific studies and sensation, and consolidated in universal aesthetic rules and guidelines. They provide a frame of reference of what is perceived as normal and pleasing, while recognizing the importance of a permissible degree of individuality (Chiche and Pinault 1994). Many of those rules date back to the classic prosthodontic literature and research on complete denture tooth setups from the early part of the 1900s (Berry 1905; Williams 1914). A more focused approach to define aesthetic guidelines for complete denture fabrication occurred in the second half of the 1900s (Pound 1951; Frush and Fisher 1958; Dahlberg 1965), funneled by an increasing demand for dental and smile attractiveness (Goldstein 1969). Subsequently, several key studies and classifications that further specified and standardized the assessment and planning of dental treatment in the aesthetic zone were published (Chiche and Pinault 1994).

The correlation between the dental and facial midline is often the first parameter in a dental aesthetic evaluation (Miller et al. 1979). Tjan et al. (1984) classified smiles by the amount of tooth structure displayed when a person is smiling. In this classification, 70% to 100% of the maxillary anterior teeth, the premolars, and the tips of the interproximal papillae are displayed in an average smile. Greater amounts of gingival display are considered a "high" smile line, while less tooth display is classified as a "low" smile or lip line (Tjan et al. 1984; Passia et al. 2011). In the late 1950s, Frush and Fisher (1958) were first to investigate harmony between the curve of the anterior teeth, the "incisal line," and the lower lip, which should be parallel. While average dimensions of anterior teeth are well documented in the literature (Chiche and Pinault 1994), their shapes, morphologies, and surface texture can differ substantially, and several attempts were made to define a universal concept for anterior tooth shape selection (Nold et al. 2014). Williams (1914) concluded that human teeth could be classified into 3 principal shapes: rectangular, triangular, and ovoid. He suggested that tooth shape should be determined by the facial outline. However, a recent study that compared 3-dimensional (3D) tooth and face scans could not find a correlation between face shape and anterior tooth shapes (Wegstein et al. 2014). While a similar 3D analysis suggested subtle differences between the anterior teeth in males and females (Horvath et al. 2012), the long-standing paradigm that women should have round, soft, delicate teeth (ovoid) and men should have square, angular teeth has never been verified, and there is no scientifically validated protocol on how to select a patient's tooth shape. Tooth proportions, tooth-to-tooth proportions, tooth positioning, axial inclination, and arrangement are parameters that have been studied extensively (Levin 1978; Preston 1993). Special attention has been placed on the 3D position and angulation of the maxillary central incisors (Pound 1951). The most important determinant in aesthetic denture setups and smile designs is the position of the incisal edges of the central incisors when the mandible is at rest (Vig and Brundo 1978; Chiche and Pinault 1994).

Several recent studies have investigated the difference between lay and professional opinion on dental aesthetic parameters. Thresholds of aesthetic acceptability for dental aesthetic problems by laypeople were defined in recent systematic reviews (Parrini et al. 2016; Del Monte et al. 2017). These thresholds and acceptable variability of smile parameters should be considered when diagnosing and planning dental aesthetic treatment. They also demonstrate that there is no definition of optimal aesthetics and that the application of rigid rules and scientific method is complicated (Sarver and Ackerman 2003).

To fulfill aesthetic goals in respect to tooth position and angulation, a large number of aesthetically compromised patients require orthodontic treatment (Riedel 1950; Peck and Peck 1970). Edward Angle (1855–1930) made orthodontics the first dental specialty that focused on aesthetics and function (Turley 2015). Since then, orthodontics underwent significant progressions, moving from treatment philosophies that often included extraction therapy (Cryer 1904; Tweed 1944–1945) toward expansion and molar distalization (Haas 1965). Since the 1990s, digital technologies have facilitated interdisciplinary planning and execution of complex restorative-driven orthodontics and orthognathic surgery (Ackerman and Ackerman 2002) and facilitated the success of current clear aligner treatment (Kesling 1946; Rossini et al. 2015).

Tooth Color

Analyzing (Clark 1931), selecting (Gill 1950), communicating, and ultimately applying the proper color when restoring or replacing teeth with dental materials (Crisp et al. 1979) has always been among the greatest challenges in aesthetic dentistry.

The color of teeth is determined by intrinsic and extrinsic colorations. Intrinsic color is related to light scattering and absorption of the enamel and dentin, while extrinsic color is determined by the absorption of materials onto the tooth surface (ten Bosch and Coops 1995). They are a result of optical properties related to transmission, absorption, scattering, and reflection of light. The color of a tooth is mainly determined by the color of the dentin, while enamel seems to play only a minor role through scattering of light (ten Bosch and Coops 1995). Demineralization and dehydration have a significant impact on tooth color (Joiner 2004). While most studies could not identify significant differences in tooth color between males and females, there is a significant tendency of natural teeth to become darker and more yellow with increase in age (Joiner 2004).

The perception of color is influenced by the light source, the object being viewed, and the observer (Joiner 2004). It is therefore difficult to communicate color with others, and several color scales have been developed for that purpose. Clark (1931) was among the first to attempt to organize tooth colors. In the same year, the Commission Internationale de l'Eclairage (CIE) developed a system to quantify color and calculate tristimulus values, which represent how the human visual system responds to a given color (CIE 2004; Joiner 2004). The first dental shade guides with a rational arrangement of shade tabs were introduced in the 1950s (Vichi et al. 2011). In the early 1970s, Sproull (1973a, 1973b, 1974) described challenges and recommendations for tooth color assessment and matching of dental materials. The CIE*Lab** system, introduced in 1976 and 1978 (CIE 2004), was first to express color by numbers and calculate differences in relation to visual perception. It is based on the theory of color perception through 3 separate color receptors (red, green, and blue) in the eye (Joiner and Luo 2017). For color communication, the most commonly used is the HSB/HSV system. It defines colors in the dimensions of value, hue, and chroma, which can be correlated to the CIE*Lab** and other systems. Several other formulas have been developed in the meantime to address perceptional nonuniformities (Joiner and Luo 2017) and to better assess color difference thresholds of dental materials such as ceramics (Ghinea et al. 2010). In general, matching the complex intrinsic optical properties and color of natural teeth with dental materials remains a great challenge (Lee et al. 2010) and may never be completely possible. The ultimate appearance and color match of dental materials are not only determined by their specific properties but influenced by the color of supporting teeth and core materials and, for all-ceramic restorations, the luting agent applied for insertion (Vichi et al. 2011).

In addition to value, hue, and chroma, secondary optical properties, such as translucency, opacity, iridescence, surface gloss, and luminescence (mainly fluorescence and phosphorescence), determine the appearance of a tooth. Charles Pincus (1938), one of the pioneers in aesthetic dentistry, emphasized the importance of light and light reflection on the perception of tooth form and surface texture early on. Stübel (1911) was first to describe the fluorescent properties of teeth when irradiated with ultraviolet light. Benedict (1928) demonstrated that dentin has much greater fluorescent properties than enamel. However, the contribution of fluorescence on the visual perception of tooth color under normal light conditions has been questioned (ten Bosch and Coops 1995).

Modified shade-matching techniques (van der Burgt et al. 1985) as well as technologies to measure color (Miyagawa and Powers 1983; Seghi et al. 1989) have been described to simplify and standardize color assessment and matching. Visual shade matching with commercial shade guides is most common yet considered inconsistent and subjective, as it is influenced by lighting, age, sex, eye fatigue, and visual capabilities (Joiner and Luo 2017). As new and more accurate shade guides were developed (Paravina et al. 2002), special lights and training seem to significantly improve shade-matching ability (Clary et al. 2016). Color-measuring instruments and systems have become increasingly popular, especially in dental research. These include spectrophotometers, colorimeters, spectroradiometers, and digital image analysis techniques. When applied properly, digital imaging systems for color measurements are comparable to spectrophotometry while providing additional information and measuring appearance attributes beyond intrinsic color (Joiner and Luo 2017).

Tooth Whitening

Probably the most cost-effective and least invasive procedure to improve dental aesthetics is vital bleaching of teeth (Haywood 1991, 1992), which involves the application of an oxidizing agent for the purpose of removing color-producing stains or chromogens within the tooth. The specific mechanism of action is believed to entail the breaking up or oxidation of stain molecules or chromophores into colorless compounds.

Dental bleaching has been performed since the late 1800s (Bogue 1872) with a variety of oxidizing agents, including chlorine, oxalic acid, potassium cyanide, and others. However, hydrogen peroxide, first believed to be reported for dental bleaching in the late 1800s, has been the preferred material for vital bleaching ever since (Fisher 1911). By the early 1900s, in-office vital bleaching involved the use of heat to potentiate the dissociation and effectiveness of the hydrogen peroxide whitening agent (Fisher 1911). This technique remained the predominant method for tooth whitening until the introduction of a "dentist-prescribed, home-applied" approach called "nightguard vital bleaching" in 1989 (Haywood and Heymann 1989). A vacuum-formed custom plastic tray is used to deliver a carbamide peroxide whitening agent. Although this technique was discovered quite by accident in the late 1960s, it was not until the late 1980s and early 1990s that it became widely used. In 2001, a unique over-the-counter tooth-whitening strip system was introduced for the application of a low-dose hydrogen peroxide whitening active with thin disposable plastic strips (Sagel et al. 2000). This trayless tooth-whitening delivery system has become very popular and shown in clinical trials to be both safe and effective (Gerlach et al. 2009).

Hydrogen peroxide is still being used for direct application to teeth for tooth whitening, as are sodium perborate (Spasser 1961) and carbamide peroxide, both of which produce hydrogen peroxide as a reaction product to effect dental bleaching. All bleaching procedures are time and concentration dependent, with wide variations in concentrations and exposure times being employed depending on dentist and patient preferences. Vital tooth-whitening procedures with hydrogen peroxide are considered safe when used as instructed (Munro et al. 2006). Side effects and risks include increased tooth sensitivity and gingival irritation (Carey 2014). These seem more pronounced with in-office bleaching systems, which, after the first week, do not appear to have any advantage over home bleaching systems in respect to rate of bleaching or durability (Bemardon et al. 2010). Teeth can typically be lightened by 1 to 2 shades, lasting for about 1 y unless the procedure is repeated more frequently (Wiegand et al. 2008). If greater whitening is desired, restorative measures, such as laminate veneers, have to be applied.

Adhesive Restorations

For malformed, malpositioned, or slightly damaged teeth, adhesively bonded direct and indirect dental materials can restore aesthetics and create a pleasing smile with minimal invasiveness and limited sacrifice of natural tooth structure. The evolution of dental materials over the past century was described in greater detail in a recent article (Bayne et al. 2019). One of the most profound discoveries that enabled the age of "dental bonding," or adhesive dentistry, was that of acid etching by Michael Buonocore in 1955. He discovered that enamel could be treated with phosphoric acid to produce a surface capable of strong adhesion to resin, which is still the basis for virtually all clinical procedures involving enamel-resin adhesion.

The clinical application of resin into pits and fissures for the purpose of sealing teeth has since become an accepted means by which caries can be prevented (Buonocore 1970). However, it is in the realm of conservative aesthetic dentistry that Buonocore's discovery of the "acid-etch technique" likely has had the greatest impact: anterior and posterior tooth-colored restorations, direct and indirect veneers, diastema closure, periodontal splints, bonded ceramic restorations, resin-bonded fixed dental prostheses, and many more, even extending into the adhesion of CAD/CAM restorations today (computer-aided design/manufacturing).

The more complex mechanisms of dentin bonding were evaluated and specific dentin bonding agents developed (Brudevold et al. 1956). Nine years later, Bowen (1965) introduced a specific dentin adhesive solution. Second-generation systems of the late 1970s incorporated halophosphorous esters of unfilled resins. Protocols including acid etching of dentin to partially remove the smear layer, as well as application of a hydrophilic resin phosphate primer and an unfilled adhesive resin, were considered the next generation of dentin bonding agents. While the "hybrid layer" was a key finding (Nakabayashi et al. 1982), bonding to smear layer–covered dentin was not very successful before 1990 (Tao et al. 1988). Complete removal of the smear layer was part of fourth-generation bonding systems through application of a total-etch technique (Kanca 1991). Fifth-generation adhesives, the 1-bottle systems, comprise a separate etch-and-rinse phase, followed by the application of a combined primer-adhesive-resin solution. The following generation of adhesives are referred to as *self-etch adhesives*, which do not require a separate acid-etch step, as they condition and prime enamel and dentin simultaneously by infiltrating and partially dissolving the smear layer and hydroxyapatite to generate a hybrid zone that incorporates minerals and the smear layer. The latest generation of all-in-one adhesives combines conditioning, priming, and application of adhesive resin in 1 bottle (Van Meerbeek et al. 2010).

The research breakthrough that advanced the concept of tooth-colored conservative aesthetic procedures was Ray Bowen's (1963) formulation of the BIS-GMA resin composite (bisphenol A, glycidyl methacrylate): a unique resin that would polymerize rapidly under oral conditions and could be filled with various types of ceramic particles. A wide range of new and improved composite resin materials with various compositions, shades, translucencies, viscosities, and curing modes is available today for direct aesthetic restorations. While the current scientific evidence seems to support amalgam over composite resin restorations with respect to clinical longevity in posterior teeth (Rasines Alcaraz et al. 2014), growing concerns about mercury, inadequate aesthetic properties, and the need for more invasive and retentive tooth preparations favor composite resins in today's clinical practice.

Composite resin-luting agents and adhesive technologies are widely used for bonded ceramic restorations, such as inlays/onlays, laminate veneers (Faunce and Faunce 1975), and resin-bonded fixed dental prostheses (Livaditis 1980). Some of the ceramic-bonding developments are based on early attempts to bond porcelain teeth to acrylic denture bases (Paffenbarger et al. 1967). Feldspathic and other ceramics are significantly strengthened by adhesive bonding to the supporting tooth structures with composite resins and adequate bonding agents (Fleming et al. 2006). For optimized adhesion, silica-based ceramics are pretreated with hydrofluoric acid (Simonsen and Calamia 1983) and a silane coupling agent (Semmelman and Kulp 1968). In a recent study, resin-bonded CAD/CAM feldspathic ceramic inlays and onlays revealed an 87.5% success rate up to 27 y (Otto 2017). Beier et al. (2012) estimated the survival probability of porcelain laminate veneers at 93.5% over 10 y.

Prosthodontics

Observation and geometric assessments of facial features led to the definition of aesthetic guidelines for complete denture treatment (Pound 1951; Lombardi 1973), which were similarly applied in fixed prosthodontics (Chiche and Pinault 1994).

Historically, a large variety of materials was used for removable and fixed prostheses, with ceramics providing a favorable combination of aesthetics and durability. In 1886, Charles Land (1888) introduced crowns, inlays, and onlays made from porcelain, which also became a preferred material for denture teeth (Henshaw 1904).

Soon after their invention in the early 1960s, porcelain-fused-to-metal restorations (Weinstein and Weinstein 1962) became the gold standard for fixed single- and multiunit prosthetic restorations. Over the past 50 y, developments were geared toward metal-free all-ceramic materials that offer tooth-like aesthetics with superior physical properties, even for posterior teeth. These include aluminous feldspathic ceramics (McLean and Hughes 1965) and, more recently, leucite-reinforced feldspathic ceramics (Dong et al. 1992) and lithium disilicates (Höland et al. 2000) for single-unit monolithic all-ceramic restorations. Clinical long-term success of lithium disilicate crowns is very high at 96.7% after 10 y (Pieger et al. 2014). Due to their limited physical properties, lithium silicate ceramics are not ideal for multiunit fixed dental prostheses, which have shown a 30% failure rate at the same follow-up.

Glass-infiltrated (Degrange et al. 1987) and densely sintered (Andersson and Odén 1993) aluminum oxide ceramics were deemed the first "high-strength" ceramic materials with excellent clinical success (Fradeani et al. 2002; Oden et al. 1998). As for earlier generations of polycrystalline zirconia, the strongest ceramic in dentistry (Christel et al. 1989), application of veneering porcelains was necessary to create natural aesthetics. While bilayer porcelain-fused-to-zirconia restorations initially seemed to be prone to ceramic chipping (Sailer et al. 2006), more recent developments of adequate veneering porcelains and techniques greatly reduced such complications (Ozer et al. 2014). Recent high-translucent and polychromatic zirconia compositions (Zhang 2014) are used for monolithic restorations (Johansson et al. 2014). Current all-ceramic materials facilitate a variety of noninvasive and highly aesthetic treatment options, especially in combination with adhesive technologies, such as all-ceramic resin-bonded fixed dental prostheses (Kern 2005) with excellent long-term success (Blatz et al. 2003; Blatz et al. 2018). Adhesive resin bonds to metal alloys and high-strength ceramics are more difficult to achieve than etchable silica-based ceramics and require different surface treatment methods and special bonding agents (Blatz et al. 2018).

Significant material developments have facilitated improved aesthetic outcomes in implant prosthodontics, especially with the introduction of high-strength ceramic implant abutments in the early 2000s (Yildirim et al. 2000). Ceramic implant restorations and components provide better aesthetic outcomes than metal abutments and porcelain-fused-to-metal restorations (Jung et al. 2007; Jung et al. 2008). Clinical studies demonstrate high success rates of ceramic and especially zirconia abutments (Glauser et al. 2004).

Prosthetic management of aesthetic soft and hard tissue defects with pink acrylic or porcelain may become necessary when surgical interventions are not possible or reach their limitations in terms of outcomes and longevity (Malament and Neeser 2004). This is especially true in the completely edentulous jaw, where fixed and removable implant-supported overdentures have been used for decades to restore aesthetics and function (Desjardins 1992).

Dental Implants

The discovery of osseointegration and invention of endosseous dental implants in the 1960s (Brånemark 1983) have revolutionized the field of prosthodontics, providing anchorage and retention for crowns (Andersson et al. 1998) as well as fixed and removable prostheses (Adell et al. 1981) with very high long-term success rates (Tomasi et al. 2008). Aesthetic outcomes have become increasingly important for implant restoration success in the anterior jaws (Belser et al. 2004) with the goals to closely replicate the natural dentition and create a harmonious soft and hard tissue architecture (Garber 1995).

For more information on this topic, the evolution of oral implants in restorative dentistry is detailed in another *Journal of Dental Research* Centennial article (Lang 2019).

Periodontal, Oral, and Maxillofacial Surgery

Guidelines for "white" tooth aesthetics should always recognize the importance of "pink" aesthetics. These comprise the adjacent gingiva and soft tissues as well as the supporting bone, which serve as a natural frame of the teeth. Several localized and general factors influence the aesthetic appearance, morphology, and health (Stillman 1921) of the gingival tissues, many of them iatrogenic (Löe 1968). Surgical and nonsurgical techniques to create healthy, harmonious, and aesthetic hard and soft tissue support for natural teeth or their replacements are therefore essential for clinical success (Abrams 1980).

Modern facial reconstructive surgical procedures were introduced in the early 1900s during World War I (Davis 1946) and included reconstruction of all lost tissues of the face. With a growing demand for aesthetics, medical surgical principles and procedures were applied to reconstruct soft tissue and bone within the oral cavity (Allen et al. 1985; Allen 1988; Rosenberg and Cutler 1993). Intraosseous dental implants (Brånemark 1983) have become invaluable tools to replace missing teeth. They often necessitate reconstruction of sufficient bone height and width to provide an adequate foundation and properly support prosthetics.

Soft Tissue Deformities

Aesthetic soft tissue defects are often related to root surfaces or residual ridges and can be reconstructed with a free soft tissue graft (Soehren et al. 1973), flap procedure, or a combination thereof (Sanz and Simion 2014). McGregor and Morgan (1973) introduced various soft tissue flap designs to treat aesthetic tissue defects. They were cutaneous, adjacent to the defect, and either partial or full thickness. Subsequently, they were classified by mode of transfer—for example, rotational or advanced (Bahat et al. 1990).

Miller (1985) published a classification of various gingival recession defects on root surfaces. Multiple grafting techniques have been described since then (Allen 1994), with the subepithelial connective tissue graft (Langer and Calagna 1982) providing the most favorable outcomes and soft tissue reconstruction over teeth, edentulous crests, and dental implants (Tatakis and Trombelli 1999). Soft tissue substitutes, such as acellular dermal matrix grafts, have become popular to avoid surgical preparation of a donor site and the associated morbidity (Allen 1994).

Bone Reconstruction of Deficient Ridges

Guided bone regeneration, typically a combination of a membrane and bone graft material, has been successful to treat limited bone defects around teeth and implants (Dahlin et al. 1988). Reconstruction of a large osseous ridge defect typically necessitates more extensive augmentation with autologous bone or bone substitute and coverage with soft tissue. Tissue can be generated by flap advancement or controlled tissue expansion (Bahat and Handelsman 1991). Different bone graft materials have been developed over the years, including autografts (Boyne and James 1980), xenografts (Pinholt et al. 1991), allografts (Jensen and Sennerby 1998), and alloplasts. Graft technique and material selection depends on the type of restoration and the specific behavior of the graft relative to physiologic loading challenges and craniofacial changes (Daftary et al. 2013). The current evidence is not clear on which augmentation technique and material are most successful in the long term, but complications are rather common (Esposito et al. 2009). The facial appearance of the lower two-thirds of the face depends on the scaffolding effect of the mandibular and maxillary ridges. Their reconstruction has much wider implications.

Today, less invasive therapies, new biomaterials, stem cell therapy, as well as recombinant tissue growth factors achieve regeneration of the oral tissues and, at the same time, reduce morbidity while improving patient comfort (Dawson et al. 2019).

CAD/CAM Technologies

The invention of computer-assisted diagnostic, treatment-planning, design, and restoration fabrication technologies had a significant impact on aesthetic dentistry through digitization and simplification of key clinical and laboratory steps (Touchstone et al. 2010). A dental CAD/CAM device that included both an optical scanner and a numerically controlled milling machine was first demonstrated in 1985 (Duret et al. 1985). The first commercial chairside CAD/CAM system was developed around the same time (Mörmann 2006) and could fabricate, on the basis of an optical scan, a tooth-colored ceramic dental restoration in the dental office the same day.

Over the last 30 y, laboratory-based CAD/CAM systems that include optical or mechanical scans of a cast, digital restoration design software, and a CAM system either in the dental laboratory or at a centralized milling center have become standard in dental technology (Rekow 1987). They provide predictable, precise, and reliable restorations from materials with improved aesthetic and physical properties. CAD restorations can be modified, multiplied, and realized in a variety of materials, from metal alloys, waxes, acrylics, and polymers to composite resins and various ceramics. While early CAD/CAM systems were limited to inlays, onlays, and single units (Mörmann 2006), current systems have the ability to fabricate restorations from single units to fixed and removable full-arch prostheses with laboratory-based CAD/CAM systems. Currently, the most prominent and accurate CAM method is subtractive through milling (Andersson et al. 1996). However, additive manufacturing techniques (Horn and Harrysson 2012) such as 3D printing will become the fabrication processes of choice for all types of materials and restorations. While there are still significant limitations with respect to accuracy as well as material options and properties, developments of technologies to print metals and ceramics even for dental treatment are well underway (Alharbi et al. 2017).

Digital Smile Design

Classic aesthetic evaluation and treatment guidelines were based on 2-dimensional measurements. Clinical studies that include 3D surface analyses of scanned teeth and faces revealed findings that were often in contrast to traditional paradigms and "classic" studies on aesthetic parameters (Horvath et al. 2012; Nold et al. 2014; Wegstein et al. 2014). Faces and smiles are not absolutely symmetric but rather dynamic (Hambridge 1921), which has to be considered when natural and harmonic smiles are designed and planned (Silva et al. 2019).

Cone beam computer tomography as well as intra- and extraoral optical scanners allow for detailed 3D evaluation of all oral structures and tissues. Specific computer programs and software tools enable digital planning and visualization of anticipated aesthetic outcomes while creating a pattern for the subsequent restorative, orthodontic, surgical, and multidisciplinary treatment (Zimmermann and Mehl 2015).

One of the first articles that introduced digital smile analysis and design was published in 2002 (Ackerman and Ackerman 2002), featuring a smile dynamic analysis through videography. Computer programs such as PowerPoint, Keynote, and Photoshop (McLaren et al. 2013) enable clinicians and technicians to draw aesthetic reference lines onto patients' face-and-smile photos on the computer screen, instead of drawing on printed photos or stone casts. Several computer programs were developed in the mid-2000s to simplify these steps and project idealized and customizable tooth proportions and shapes onto the digital image (Zimmermann and Mehl 2015). In 2008, the first digital smile design protocol was developed, fully facially guided through a series of facial, extraoral, and intraoral photos (Coachman et al. 2017). Merging 2-dimensional photos with 3D digital models allowed transition to a completely digital format to verify and develop aesthetic parameters in 3 dimensions (Coachman and Paravina 2016). Applying digital scan files of natural teeth, tooth morphologies, and smiles from a natural algorithms library to simplify the "digital wax-up" facilitates customized and natural aesthetics, independent of the aesthetic perception of the clinician or the wax-up skills of the dental technician. Digital smile design tools are beneficial to any dental specialty related to facial and dental aesthetics: restorative dentistry (Coachman and Paravina 2016), periodontics (Arias et al. 2015), orthodontics (Levrini et al. 2015), prosthodontics (Pozzi et al. 2018), and oral surgery (Rojas-Vizcaya 2017). Likely discrepancies between the digitally designed and the actual clinical outcome must be taken into consideration to not create unrealistic expectations. It is therefore critical for any aesthetic procedure that the planned situation be visualized with an intraoral mock-up (Sancho-Puchades et al. 2015), ideally documented and evaluated through dynamic video capture instead of static smile photos.

Present and Future of Aesthetic Dentistry

There are several software programs that integrate all diagnostic, treatment-planning, design, and digital manufacturing steps in 1 system (Zimmermann and Mehl 2015). Natural tooth-and-smile algorithm libraries facilitate aesthetic outcomes that are superior to hand-built wax-ups or computer-generated shapes. Designing teeth and smiles based on dynamic facial and lip analyses increases predictability and aesthetic outcomes. Three-dimensional face scans are merged with intraoral scans, model scans, and cone beam computer tomography scans in a truly digital workflow. New digital smile design software also incorporates digital articulators and jaw-tracking devices to include functional parameters into the digital-planning and treatment process. Current smartphones and other mobile electronic devices have the ability to make 3D face scans. Merging such scans with other diagnostic information in a specific aesthetic design application (app) platform allows the clinician and dental technician to design cases even on mobile devices (Daher et al. 2018). Some of these apps are quite sophisticated, with many steps already automated and transferable to a laboratory CAD software.

Aesthetics, smile design, and the perception of beauty and harmony are often subjective and dependent on the clinician or dental technician. With advanced digital tools, patients are able to select natural teeth and smiles that match their personal preferences and expectations. They can try these virtually or with a physical mock-up. Virtual and augmented reality apps can superimpose smile designs into real-time dynamic augmented reality simulations.

In the future, machine learning and artificial intelligence will automate most, if not all, aesthetic evaluation, planning, design, and treatment processes to provide customized dental care that is truly patient centered, natural looking, and in harmony with facial and other features. However, the ultimate test for the aesthetic and functional success of dental treatment still occurs clinically in the oral cavity.

Beyond digital planning and design tools, new treatment concepts, manufacturing processes, and advanced biomaterials will further enhance the functional and aesthetic long-term success of oral health care. In the long term, bioengineering and the ability to regenerate and grow teeth, soft tissues, and bone may eliminate these tools and restore or create dentofacial aesthetics in a truly natural way (Ikeda and Tsuji 2008) if they can be offered in an economically affordable manner.

The future of aesthetic dentistry is to reconnect with nature and to develop tools that replicate and create the variations found in natural beauty, independent of the skill set of a clinician or dental technician and accessible to every individual patient.

Conclusion

Aesthetic dentistry is part of any clinical specialty area and has seen tremendous progress over the last 100 y, especially with the application of digital tools and workflows that facilitate a customized 3D interdisciplinary approach to smile design and treatment execution.

Author Contributions

M.B. Blatz, contributed to conception and data acquisition, drafted and critically revised the manuscript; G. Chiche, O. Bahat, R. Roblee, C. Coachman, H.O. Heymann, contributed to data acquisition, drafted the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

Acknowledgments

The authors express their appreciation for the contributions of Dr. Julian Conejo, Department of Preventive and Restorative Sciences, School of Dental Medicine, University of Pennsylvania, Philadelphia, PA, USA; Sean Han, certified dental technician, Master's Arch Dental Laboratory, Chandler, AZ, USA; and Dr. Ion Zabalegui, visiting professor, Department of Periodontology, Universidad Complutense Madrid, and private practice, Bilbao, Spain. The authors received no financial support and declare no potential conflicts of interest with respect to the authorship and/or publication of this article.

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