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Trends in materials science from the point of view of a practicing dentist

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Abstract

In the last 15 years remarkable changes in restorative dentistry occurred. The use of amalgam dropped dramatically, also the use of different types of alloys. The reasons were beside aesthetics the controversial discussion about amalgam and metal toxicity and environmental pollution. This shift did accelerate the development and use of composite resins and ceramic materials for dental restorations. Simultaneously to this development, new concepts in minimally invasive dentistry as well as in adhesive dentistry were introduced and improved.

For small and medium sized cavities meanwhile composite resins are the first choice, whereas for large defects, crowns and bridges full ceramic restorations increased in number enormously. Most important questions in clinical practice are the handling of the material and the longevity of the restoration. Recent reviews show that composite resin restorations can compete with amalgam and indirect ceramic restorations but gold restorations are still the best in long-term performance.

Main problems in clinical use are fractures, wear, gap formation and secondary caries, postoperative hypersensitivity and technique sensitivity. In contrary to earlier decades in the last 10 years the main reason for failure with composites is no longer secondary caries but nowadays fractures. Chipping of material and bulk fractures are also the most frequent reasons in ceramic restorations which limits the range of indication and there is still a need for improvement. But in general the patients are highly satisfied with these new adhesive and tooth coloured restorations.

Keywords: Composite; Ceramic; Longevity; Failure; Fracture

1. Introduction

In the last 15 years remarkable changes in restorative dentistry occurred. The use of amalgam dropped dramatically, also the use of different types of alloys. The reasons were aesthetic aspects, the controversial discussion about amalgam and metal toxicity but also environmental pollution by mercury waste. In Norway with the beginning of 2008 the use of amalgam was extremely restricted (with the exception of patients with allergy against resins and children treated in general anaesthesia). That means that it is nearly abandoned. Denmark and Sweden have obviously plans of similar steps in 2008.

These increasing restrictions in many countries did accelerate the development and use of composite resins and ceramic materials for dental restorations in the last 20 years. Concurrently to this development, new concepts in minimally invasive dentistry as well as in adhesive dentistry were introduced and improved. Also the interest and importance in prevention, endodontology and implantology increased tremendously and simultaneously numbers of and acceptance for removable partial and full prostheses decreased.

For small and medium sized cavities meanwhile composite resins are the first choice, whereas for very large defects, crowns and bridges the number of all ceramic restorations increased enormously. This paper focuses on the current trends of composites and ceramics mainly in restorative dentistry and resulting deficiencies or problems which show the needs for future developments.

2. Longevity of restorations and reasons for failures

The most important issue in clinical practice is besides the maximum preservation of tooth structure, easy handling of the material and low technique sensitivity the longevity of the restoration.

Conrad et al.[1] published a systematic review about current ceramic materials and systems (onlays, crowns, fixed partial denture prosthesis) with clinical recommendations. Typical sur-

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vival rates for all-ceramic restorations after 2–5 years in service ranged from 88% to 100% and after 5–14 years between 84% and 97%. When classifying complications they found that fractures of the ceramic material were the most frequently reported complications resulting in failure. Further reasons for failure were endodontic treatment followed by debonding, tooth fracture and caries. A lot of minor complications which were not calculated as failure were reported; by far most often chipped ceramic and endodontic therapy but also marginal deficiencies, decementation or debonding and caries. Between the authors there were different definitions of failure which influences the longevity data significantly.

Since the year 2000 several reviews about longevity of different groups of filling materials were published.[2–5] The annual failure rates of all groups of investigated materials (without GIC or other cements) are in accordance with the recommendations of ADA (not more than 2.5%). The latest review[6] shows that the longevity of composite resin restorations is in the same range as amalgam and indirect ceramic restorations. Pooling all clinical studies with an observation period of at least 2 years amalgam and ceramic showed a certain tendency for better performance and gold restorations still were the best. Analysing the long-term performance (studies with at least 10 years duration) similar trends can bee seen but in studies with direct comparison only gold inlays performed significantly better. Three publications with direct comparison of amalgam and composite found also no differences (Tables 1 and 2).[6]

Longevity is influenced by the operator, the patient and the material. Bogacki et al.[7] published that the survival rate after 7 years for amalgam was 93%, for composite 92% (when the patient stayed with the same dentist). Despite only 1% difference this was significant as they used more than 300,000 multisurface restorations of an US insurance claims database. When the patients changed the dentists the survival rate dropped to 61% for amalgam and composite as well.

Main reasons for failures of restorations (fillings, inlays/onlays) are fractures of restorations or teeth, gap formation and secondary caries, marginal ditching and wear, postoperative hypersensitivity and endodontic treatment. Reasons for failures of amalgam fillings were mainly cracks and tooth fractures (28% of all failures), secondary caries (20.9%) and loss (20.8%) or fracture (15%) of fillings. Composite fillings failed most frequently by fracture of filling (23.8%), secondary caries (20.7%) and loss of restoration (17.2%) whereas ceramic inlays/onlays 50.7% failed because of fractures of the ceramic. For gold inlays loss of restoration (25.4%) and secondary caries were diagnosed most frequently. (Table 3; Figs. 1a–c and 2).[6]

In contrary to earlier decades in the last 10 years the main reason for failure with composites is no longer secondary caries but nowadays fractures.[6] For direct composites indication was obviously extended to larger cavities with an increase of restoration fractures. Chipping of material and bulk fractures are by far the most frequent reasons in ceramic restorations which limits the range of indication and there is still a need for improvement, too (Fig. 2). But in general the patients are highly satisfied with these tooth coloured restorations.

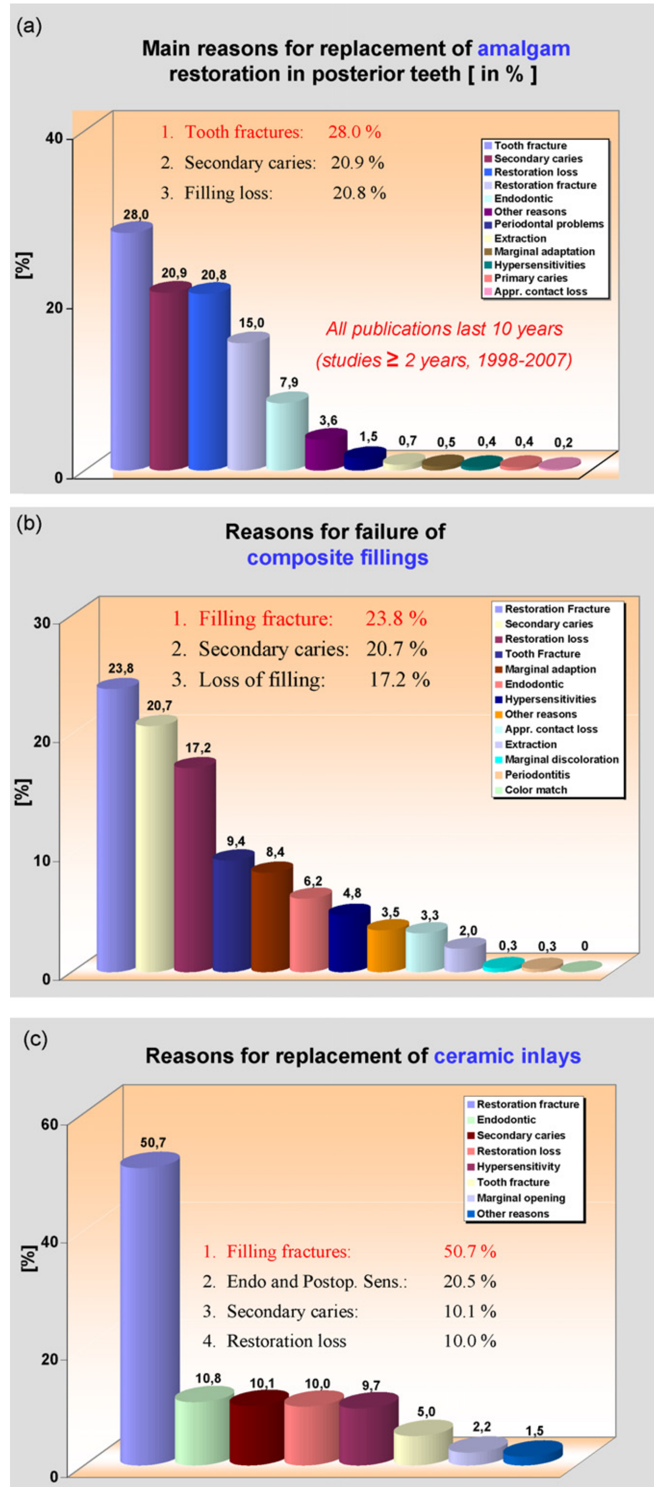

Fig. 1. Main reasons for failure of amalgam, composite and ceramic restorations. Mean of relative number (%) of failures of each study. Tooth fractures include tooth cracks, marginal enamel/dentin fractures and cusp fractures.

No serious side effects of specific materials are published in the literature also not in long-term studies. But the description of number and reasons for failures is frequently imprecise or not given. In the future a more detailed description of reason for failure is absolutely necessary.[8] Therefore for future studies

Table 1
Results of all clinical studies with an observations period of at least 2 years (number of studies and Median of annual failures rates) in comparison to clinical studies with an observations period of at least 10 years

Comparison of studies ≥2 J. and ≥10 J. (AFR in %)					
Material	*N*	Median AFR ≥2 J.	*N*	Median AFR ≥10 J.	Difference median
Amalgam	9	1.2	4	1.5	+0.3
Composite	46	1.9	13	1.9	0
Composite inlay	9	2.2	3	1.6	−0.6
Lab ceramic inlay	23	1.6	4	1.3	−0.3
CAD/CAM ceramic inlay	8	1.5	4	1.1	−0.4
Gold inlay	8	0.5	4	0.5	0

and publications the recommendations of CONSORT and FDI SCIENCE COMMITTEE PROJECT 2/98 should be followed.[8] In the biological category ratings should include postoperative hypersensitivity, pulp vitality, and the recurrence of previous pathology such as caries, erosion, abrasion/attrition or abfraction at the margins. A careful analysis of the hard tissues is also required, including evaluation of tooth integrity and recording any enamel or dentine cracks at the restoration margins. Periodontal tissue health should be analysed if the restoration is adjacent to the gingivae. Also the possibility of local and systemic side effects should be checked and reported routinely. Only with appropriate criteria in clinical evaluations reasons for failure as well as side effects can be checked and analysed reliably.[8]

In animal experiments the uptake, distribution, metabolism and excretion of monomers/comonomers were investigated. Released monomers/comonomers from composite resins can enter the intestine by swallowed saliva and after uptake monomers/comonomers can be metabolized to CO_2 and to the toxic compound epoxymethacrylic acid.[8–12]

In vitro studies revealed cytotoxic, genotoxic, mutagenic, estrogenic, and teratogenic effects of composite components.[13,9,14–19] Therefore before, during and after the development and introduction of new restorative materials research should also reflect on the local and systemic biocompatibility and the resorption and metabolism of the materials as well. Ceramics are rated as more biocompatible than all other restorative materials but it has to be taken into account that ceramic restorations have to be luted with resins or cements. One problem with ceramic still is that the restoration needs a little bit more reduction of tooth structure to get the required minimum thickness of the restoration. This may lead more often to pulpal irritation and inflammation. In ca. 10% of teeth with crowns pulp necrosis occurred. Tougher and thinner ceramic could contribute to better even biological situations and healthier pulps.

2.1. *Bioactive materials*

Since more than 20 years bioactive materials including bone morphogenetic proteins (BMP) and growth factors (GF) are not only discussed in periodontology, implantology and oral surgery but also in restorative dentistry.

Glass ionomer cements (GIC) are releasing fluoride and this can reduce caries adjacent to restorations (secondary caries) and on the proximal contact site of neighbouring teeth. One decade ago smart materials which released Ca^{2+} and OH^- ions were introduced to reduce secondary caries.[20,21] Also composite materials with antibacterial admixtures as chlorhexidin-digluconate (CHX) or antibacterial adhesives were developed.

But the clinical benefits still have to be shown more clearly. One disadvantage of resin materials with release of substances is the higher water sorption of the material followed by expansion and increased degradation and fatigue. Expansion by water uptake led to destructive crack initiation and propagation with cusp fractures which caused even tooth loss in several cases and these materials had to be withdrawn from the market. In general the mechanical properties of these ion-/drug-releasing materials showed accelerated aging and more fractures and wear.

In endodontology the gold standard for pulp capping is still calcium hydroxide. But regeneration of pulp with dentin bridging by GF and BMP covered and sealed with adhesive restorations could be a future option. Regeneration and replantation of the whole tooth is already discussed but it takes too much time (years) and many problems beside the costs are still unsolved. That will probably be no option in the next decade.

Table 2
Extra long clinical studies with direct comparison of amalgam and composite with an observations period of at least 10 years

All studies (1998–2007) with direct comparison of amalgam vs. composite (observation period ≥ 10 years)			
First author	Years	Amalgam AFR (%)	Composite AFR (%)
Opandam 2007	10	2.1	1.8
Van Nieuwenhuysen 2003	16	1.8	1.9
Mair 1998	10	0.6	0.7
Median	10	1.8	1.8

No difference can be seen in the median of annual failure rates.

Table 3
Reasons for failure distinguished between the different groups of materials in reference to Table 1

Reasons for failure (%), all studies ≥ 2 years 1998–2007						
Material	Observ. years median	Functional		Biological		
		Filling fracture	Loss of fillings	Tooth fracture/cracks	Secondary caries	Endodontic
Amalgam filings	8	20.8	15	28	20.9	7.9
Composite fillings	4.5	23.8	17.2	9.4	20.7	6.2
Composite inlay	5	30.2	1	15.2	16.4	15.6
Ceramic inlay/onlay	6	50.7	10	5	10.1	10.8
Gold inlay/onlay	8	0	25.4	7.9	23.5	6.9

Note that only the main reasons are listed and therefore failures do not add up to 100%.

In periodontology and oral surgery bone substitutes are often required and different types e.g. Bioglass™ are already available. Healing of implants and early loading is mainly influenced by the material, surface treatment (e.g. machined, etched or blasted) and size/types of surface pores. Coating with organic substances (enamel-matrix proteins, BMP etc.) can accelerate healing.

2.2. Indication of ceramics in endodontology and implantology

Severe damaged non-vital teeth require the build up with a post and a core material. Metal posts (steel or titanium) are best in strength especially for roots which are needed as abutments for bridges. But these metal posts are often causing root fractures under load which make the extraction of those teeth necessary. Nowadays adhesively luted zirconium oxide ceramic or glass fibre posts are preferably used but numerous fractures of the posts are meanwhile documented. As broken zirconium oxide ceramic posts usually cannot be removed from the root canals the teeth are also lost. Before ceramic materials will be recommended in that indication higher strength is still required. Therefore at present adhesively luted glass fibre posts are used most frequently.

The same is true in implantology. Titanium implants are mostly used but in anterior areas sometimes causing aesthetic problems. Ceramic implants have already been used since 3 decades (e.g. Tübinger implant). The disadvantages of the ceramic implants are larger diameters which are not indicated in thinner alveolar bone ridges and also fractures of the implants. If a fracture of the implant occurs, removal of the broken but well attached implant creates often large defects and is then a disaster for the bone. Before placement of a new implant is possible longer periods of bone regeneration have to be awaited maybe in support with bone substitutes.

In general an excellent primary fit of an implant in the socket will improve the healing process and also the longevity. But implants which are placed directly after tooth extraction very often have the problem that the root cross section and the alveole is not rotund and the implant does not fit well to the geometry of the socket. With an intraoral 3-D-camera an individual shape of the implant consistent to the alveolus could be milled. A CAD-CAM optimized shape of implants to the extraction socket would increase primary fit and also earlier restorative treatment would be possible (maybe even one appointment only for implantation and restoration). Ceramic is also very interesting for implant abutments and improves mucogingival aesthetics.

2.3. Restorative dentistry

CAD/CAM-Systems can enlarge the selection of materials (e.g. HIP zirconium oxide or titanium) and guarantee a high and constant quality. Up to now restorations are produced by CNC milling devices. Very hard ceramics as zirconium oxide are milled either in the green state and sintered afterwards or in the white state which is not very economic regarding time and milling instruments. Whether for CAD/CAM restorations smaller intraoffice devices or large industry grade machines in milling centers will be more preferred in the long run has to be seen. Very important is to reduce initial scratches and grooves caused by milling or grinding procedures to inhibit crack propagation. Maybe more economic build up technologies instead of grinding/milling will prevail. Future developments should not only focus on subtractive methods as milling but also on other

Fig. 2. Typical chipping of restorative material in proximal area which is frequently seen with composite or ceramic.

techniques (additive methods as laser sintering, laminated object manufacturing etc.). The latter have less geometric restrictions as instruments of milling devices and may be less entrapments (as scratches) for fractures.

In the last years the automatic reconstruction of the occlusal table of a crown was not possible. Dentists either had to capture a 3-D-imaging from the crown before preparation (if possible) or wax-up models etc. had to be done. Recently with the introduction of the biogeneric reconstruction a big step was done and with only few occlusal points (from the tooth or from the antagonist by a check bite) the total occlusal anatomy can be generated.[22,23] This makes the process of CAD/CAM-restorations even more economic.

Reasons for failure can be classified into functional, biological and aesthetical causes. Functional reasons for failures are fracture, wear and marginal deterioration. Fractures are by far most frequent for ceramics and composites. There is a lack of valid data how much strength materials for fillings, crowns or bridges in anterior or posterior areas respectively must at least show to ensure good longevity and no or only few fractures. Clinically there are also big differences in bite force and occlusal loading between normal patients and patients with severe bruxism which were usually excluded so far from receiving ceramic or composite restorations. Comparison of our in vitro database of physical data of composites with clinical results show that for filling materials with flexural strength below 80–100 MPa much more bulk fractures occur. Degradation and fatigue will lower flexural strength over time and that has to be considered as well. Edge strength is also important as chipping of composites and ceramics occurs very frequently under occlusal load and was not well investigated in the past[24] (Fig. 2).

But strength of a restoration depends on other parameters e.g. sufficient curing, too. Many dentists do not like to cure for 40 s or longer neither for composite increments nor for luting resins for ceramic restorations. Bar code reader in curing device could facilitate to get the optimum of curing for each brand and shade without wasting time. There is a need of further development for adequate *and* fast curing but without increasing the polymerisation stress. Otherwise more gaps would result which foster biofilm accumulation and secondary caries. Gap formation can also be influenced by wrong use of adhesives.

3. Wishes of dentists and future needs

Isolation (preferably with rubberdam) is necessary when placing direct or indirect restorations with resin based adhesive materials. In many cases handling is therefore not easy and not well accepted by dentists. But contamination with blood, saliva or sulcus fluid will impede adhesion. Systems or materials which cure despite presence of moisture would therefore be of high interest. Hydroxyapatite materials for fillings to be cured with derivates of phosphoric acid may be one solution but up to now adapatation and mechanical strength is not sufficient and further development necessary.

For composite fillings long-term smoothness and strength is required. Most composites nowadays have smaller particles but to get high strength and low shrinkage it is usually a mixture of different particle sizes. The larger particles inside the composite reduce the initial lustre after a short time of use. As long as these problems are not solved it seems to be better to develop different composites for posterior (high strength) and anterior (improved aesthetic) restorations. Low shrinkage materials (e.g. Siloranes) will be of interest and should be further developed to have the possibility of bulk placement or larger increments but this must not reduce the excellent performance regarding strength and handling etc.). Removal of tooth coloured restorations with excellent colour match will be a problem of the near future. It would be helpful if composites and luting cements would be easy to detect e.g. by fluorescence and specific light.

Up to now most aesthetic ceramics provide only moderate mechanical strength. Lithium disilicate performs better and is indicated in anterior regions but is not recommended in larger posterior bridges. Also the number of fractures or chipping of veneering ceramic from core ceramic has to be reduced. The development of a high strength translucent tooth coloured ceramic would be preferable.

That could enable thinner margins with ceramic, less minimum thickness of crowns and connectors which saves tooth structure and enlarges width of indication. Also easier luting procedures are desirable.

Dentin adhesives still have a high technique sensitivity which should be reduced. Maybe combinations with (flowable) composites as self-adhesive restorative materials are advantageous including indicators for leakage and penetration of carious tissues. Coating of restorations and/or teeth with nanoparticles to achieve a lotus-effect with less accumulation of biofilms should be aimed intensively.

Having analysed signal factors of microorganism for communication in the plaque it would be well directed possible to disrupt and destroy biofilms. Monoclonal antibodies against specific bacteria (caries and periodontitis) maybe produced by salivary glands after genetically modifications. Also genetically engineered bacteria e.g. *S. mutans* could be available which do not produce acids anymore and replace caries bacteria on the tooth surface. But these developments will probably have a time span of 10–20 years and side effects in the intestinal tract etc. have to be well proven and excluded before.

Despite the success and the improved measure in prevention as well as in biology and genetic engineering there will still be a need for a lot of restorations to be done in the next decades. The demands will be excellent aesthetics, good biocompatibility and high strength for better longevity.

4. Education of students and dentists

Many failures with composite and ceramic restorations occur because many (older) dentists were not trained well for these new materials and techniques. Slogans in lectures as "think ceramic" also show that there is a need in this field for continuing education of many dentists. But there are still a lot of universities in developed countries which do not teach composite or ceramic restorations in posterior teeth to dental students and sometimes even teachers have a need for advanced training. This may lead to wrong indications (short teeth, insufficient dimension of connectors, bruxism), mistakes during preparation (sharp edges, too small minimum thickness for ceramic etc.) but also inadequate grinding and polishing of material before insertion, luting mistakes etc. In our dental school as in several others e.g. composites and adhesives, all ceramic restorations, CAD/CAM technology and implantology are included from the first year on to educate future dentists up to date but also to show them the limitations.

5. Conclusions

As the indication of direct composites was obviously extended more to larger cavities the relative number of restoration fractures (bulk fractures, marginal edge fractures and chipping) increased. Fractures are meanwhile the principal reason for failure. Therefore manufacturer should try to optimize the strength of posterior composites. As the development of composites with higher strength and better aesthetics is somewhat contradictory maybe in the future separate composites for highly esthetic direct anterior restoration (with long lasting smoothness and gloss) and for occlusal stress bearing direct posterior restorations (with high strength and low fatigue) should be further developed. For direct restorations composite resins and minimally invasive techniques will be mostly preferred by patients and dentists.

The indication of the different materials and types of restoration (direct filling, indirect inlays/onlays or crowns) in many cases is not only driven by the dentists' skills and the size of the cavity but frequently also by the patients and the reimbursement system which is also varying in different countries. Care should be taken that materials are inserted according to their registration approval and sufficiently cured not only from a functional but also a biological point of view.

The use of metal restorations is still necessary in patients with severe bruxism, for very large bridges (and many implants) but numbers of metal and PFM restorations are significantly decreasing. Aesthetics has become very important in restorative dentistry but biocompatibility is getting more and more important and will influence the future development of materials probably most significantly.

The higher costs of metals, in particular gold and noble alloys will not really be an important long lasting reason to shift more to ceramics. But CAD/CAM systems which can not only reduce the costs of dental technicians but also guarantee a high and constant quality standard with prefabricated material blocks and even a more comprehensive selection of materials (as zirconium oxide) will have more influence and push ceramic systems for indirect restorations in the future. For use in large posterior bridges, in endodontology and implantology development of ceramic with higher strength is still needed.

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