



## 5.5-year-survival of CAD/CAM resin-based composite restorations in severe tooth wear patients

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### ABSTRACT

**Objectives:** Aim of this prospective study was to assess full mouth rehabilitation of severe tooth wear patients using minimally invasive CAD/CAM resin-based composite (RBC) restorations and direct veneers by evaluating restoration survival up to 5.5-years.

**Methods:** Twenty-two patients with generalized severe tooth wear with functional and/or esthetic problems were included. Following minimally invasive preparation, CAD/CAM RBC restorations (LAVA Ultimate,3M) were adhesively luted, direct RBC veneers (Filtek Supreme XTE, 3M) were applied in the aesthetic region. Patients were recalled after 1m,1y,3y,5y and seen in between recalls by their general dentists or at the clinical study center if complaints occurred. Failures were categorized as F1 (severe deficiencies requiring replacement/extraction), F2 (localized deficiencies requiring re-cementation/repair) and F3 (small chippings requiring refurbishment/monitoring). Survival of indirect restorations was evaluated using lifetables and Kaplan-Meier-graphs, distinguishing between failure categories and tooth type (front teeth=FT, premolars=PM, molars=M). F1 + F2 and F1 + F2 + F3 failures were analyzed using Cox regression on the variables tooth type/ location, age, gender and VDO increase ( $p < 0.05$ ).

**Results:** 568 indirect restorations and 200 direct veneers in 21 patients evaluated for up to 5.5-years. For indirect restorations, 96 failures were recorded (F1:6;F2:41;F3:49) and annual failure rates were 0.29%(FT), 1.56%(PM), 2.93%(M) for F1 +F2 and 0.53%(FT), 2.42%(PM), 6.11%(M) for F1 + F2 + F3. Reasons for failure were chipping fracture (48), adhesive fracture (32), complete debonding (7), caries (4), endodontic treatment (1) and reasons unknown (documentation general dentists, 4). Molar tooth type had a statistically significantly increased probability of failure compared with front teeth and premolars for F1 + F2 + F3 ( $p < 0.006$ ). Direct veneer restorations showed 18 failures (F1:2;F2:9;F3:7).

**Significance:** Minimally invasive CAD/CAM RBC restorations combined with direct RBC veneers showed an acceptable clinical mid-term survival for restorative rehabilitation of severely worn dentitions.

### 1. Introduction

Tooth wear is a physiological process that progresses over time [1]. It is a multifactorial phenomenon based on mechanical and erosive degradation in the oral environment [2]. Tooth wear can become pathological, when chewing forces increase (bruxing, clenching, grinding, etc.) and when tooth substrates are weakened by constant or frequent erosive challenges (acidic soft drinks, reflux, bulimia etc.) causing a disbalance between attack and defense mechanisms in the oral environment [3,4]. Consequently, patients can suffer from pain due to

hypersensitivity of the revealed dentine, reduced chewing capacity and aesthetic impairments [5–7]. Unfortunately, many clinical studies exclude high-risk patients when investigating treatment options or new materials [8]. Contrarily, some research groups focus on patients with etiological risk factors and severe tooth wear as an associated consequence [9]. Based on minimally invasive intervention concepts, patients are either monitored [10], treated with direct or indirect resin-based composite (RBC) build-ups [11–13], restored with ceramic restorations [14] or rehabilitated using various tooth-colored materials [15].

Treatment using RBC materials is an established concept for

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restorations in posterior teeth. Results of a meta-analysis on direct RBC Class I/II posterior restorations showed survival of about 85–90% after ten years in situ [16], although most of the analyzed studies excluded high-risk patients. The main reasons for restoration failure requiring replacements were wear and bulk-fractures (70% of all failures) [16]. A recent review study on factors influencing the longevity of direct RBC restorations reported annual failure rates from 0.08% to 4.9% in the posterior area, including 33 studies involving patients with or without risk-factors [8]. Both latter studies agree that the choice of direct RBC material has limited to no influence on long-term survival of the restoration [8,16].

In severe tooth wear patients, direct RBC materials performed well over mid-term periods (0.5–12 years), mostly only suffering height loss by wear or repairable chipping fractures [17]. A systematic review on RBC restorations placed on worn occluding surfaces of front and posterior teeth reported annual intervention rates between 0.8% and 17.8% [18]. When only catastrophic failures of direct RBC restorations were included, 5.5-year annual failure rates of 0.4% in posterior and 0.6% in anterior restorations were recorded. Considering also repairable and polishable deficiencies as failures, annual failure rates of 2.9% (posterior teeth) and 1.7% (front teeth) were reported [11].

An indirect workflow is claimed to be beneficial for being a less time-consuming procedure and resulting in better designed approximal contact areas than direct RBC build-ups [7]. However, these factors are dependent on the practitioner's experience and skills [8]. Nevertheless, indirect RBCs for CAD/CAM manufacturing have superior mechanical properties compared to their direct counterparts, due to optimal extraoral production and polymerization processes [19]. However, following traditional preparation guidelines, indirect restorations require the removal of more healthy tooth structures for adequate design. Fortunately, in accordance with European Consensus Statement recommendations [3], reports on clinical outcomes of minimally invasive therapy concepts can be found in the literature. Edelhoff et al. [14] challenged widely recommended thicknesses for ceramic restorations and successfully reduced the material thickness of a lithium disilicate ceramic to a mean of one millimeter in load-bearing areas. The group was able to present a survival of 100% in the 103 adhesively bonded onlays in seven patients after a mean observation period of 7.9 years [14]. A retrospective noninterventional study by Torosyan et al. [7] reported on minimally invasive full-mouth rehabilitation with different materials with an overall six-year survival of 99%, showing no difference in survival between RBC or ceramic materials. Oudkerk et al. [12] evaluated a non-preparation treatment of full mouth severely worn dentition in a prospective clinical study using a polymer-infiltrated ceramic network CAD-CAM composite material. Despite a minimal mean increase of vertical dimension of occlusion (VDO) of  $0.55 \pm 0.21$  mm on the first molars, a restoration survival of 100% and a success of 93.5% (caused by eleven minor chippings and one debonding) were reported after two years [12].

Clinical follow-up investigations on CAD/CAM produced RBC restorations showed promising results after one year, with all 568 indirect restorations still being in situ, while only 22 required repair or refurbishment [13]. The aim of the current study was to assess the mid to long-term survival of minimally invasive CAD/CAM resin-based composite restorations and direct RBC veneer restorations in severe tooth wear patients up to 5.5-years.

## 2. Materials and methods

### 2.1. Study design

This prospective clinical study aimed to investigate the rehabilitation of severe tooth wear using minimally invasive CAD/CAM resin-based composite (RBC) restorations (Lava Ultimate, 3M, St Paul, MN, USA). The local medical ethics committee (CMO Arnhem-Nijmegen) stated that their approval was not necessary for this study (file nr. 2014–1252).

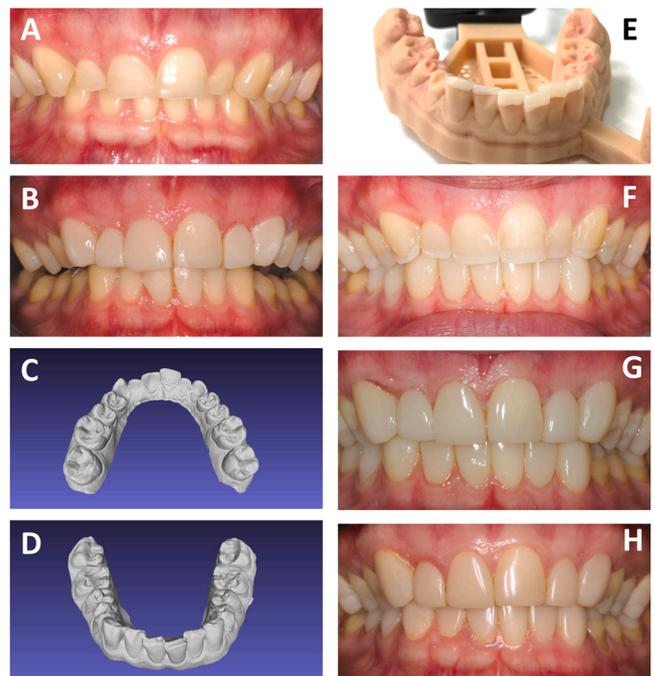
Before initiation, the study design was registered on ClinicalTrials.Gov (NCT02957734).

### 2.2. Patient selection

General dental practitioners referred patients suffering from moderate to severe tooth wear to the Radboud Tooth Wear Project (RTWP) at the Department of Dentistry of the Radboud University Medical Centre in Nijmegen (The Netherlands). Criteria for inclusion were: 1) age  $\geq 18$  years; 2) moderate to severe generalized tooth wear with functional problems and demand for treatment (TWI  $\geq 3$  = tooth wear index according to [20]); 3) full dental arches (one gap posterior region allowed); 4) aspired increase of vertical dimension of occlusion (VDO) on first molars  $\geq 3$  mm. Patients were excluded when having 1) (history of) temporomandibular dysfunction; 2) advanced periodontitis; 3) deep caries lesions; 4) multiple endodontic problems; 5) local or systemic conditions displaying a contra indication for dental procedures. No exclusion was based on individual risk factors like gastro-esophageal reflux disease, parafunctional habits, or bruxism. Informed consent was signed by all patients before being involved in the study.

### 2.3. Baseline registration

At intake, a clinical (intra-oral examination, photographs, intra-oral 3D scans (True Def IOS, 3M) and radiographic (bitewing, panoramic) examination was performed (Fig. 1A). Insufficient RBC restorations and all amalgam fillings were replaced prior to the treatment (Scotchbond Universal, Filtek Supreme XTE; 3M). Patients were scored for features of mechanical or chemical tooth wear by one researcher (LC) using intraoral 3D-scans and images, following an individualized index based



**Fig. 1.** Procedure of restorative treatments on patient LU-15: A) situation at intake showing severe wear with loss of vertical dimension of occlusion (VDO); B) unbonded resin based composite mock-ups on all upper front teeth and lower central incisors for aesthetical smile-design and estimation of possible VDO increase; C)/D) intraoral 3D-scans of the minimal invasive preparation of upper and lower jaw respectively; E) 3D-printed model presenting lingual Lava Ultimate veneers produced and fitted by dental technicians; F) situation after placement of all indirect Lava Ultimate restorations and lower front teeth direct veneers; G) completed treatment including upper front teeth direct vestibular veneers; H) photo documentation at recall appointment 5 years after treatment.

on literature [21]. The score ranged from 0 to 2 on mechanical features (similar degree of wear in all occluding sextants; imprint of mandibular front teeth on palatal surfaces of maxillary front teeth) and from 0 to 3 on chemical features (“raised restorations”; loss of convexities on the palatal surface of maxillary teeth; preserved enamel “cuff” in the gingival palatal crevice of maxillary front teeth).

#### 2.4. Restorative treatment

Four experienced dentists performed the restorative treatment according to the following protocol: The first step was buccally placed direct intra-oral RBC mock-ups on all six upper front teeth as an aesthetic smile design. After consent of the patient, increase in VDO was defined by adding RBC mock-ups palatal of upper central incisors and to lower central incisors (Fig. 1B). The situation was preserved using photographs and intraoral 3D-scans in which the mock-up on the upper front teeth served as guidance for a digital “wax-up” later by dental technicians. The increased VDO was registered with fast-setting polyvinylsiloxane silicon (Star VPS, Danville Materials, San Ramon, CA, USA) being placed in the occlusal space between the (pre)molars, with the patients closing in centric relation on the anterior mock-ups [22].

By only removing sharp edges and defining the outline, a minimally invasive tooth preparation was carried out in the following appointment. Final preparations were recorded using intraoral 3D-scans (Fig. 1C, D). Bite registration was performed in the determined increased vertical dimension using the intraoral silicon stops. Dental Technicians (Elysee Dental, Modern Dental Group, Alphen aan de Rijn, The Netherlands) generated virtual wax-ups, which were checked by the operating dentist. After approval of the respective operator, indirect RBC restorations were produced in a CAD-CAM workflow (cementation gap 80 µm, N4 + four-axis wet milling machine, VHF, Ammerbuch, Germany). No value for minimum thickness was defined but the maximal space available defined by the clinical registration was applied. Depending on the arch relation, indirect restorations on lower incisors/canines were either planned on vestibular or lingual sides (Fig. 1E). In order to avoid seating errors during placement two clinical series of preparation, impression, designing, milling and cementation of restorations were performed in succession: In the first series all incisors/canines, second premolars and second molars were restored. In the second series, the remaining first premolars and first molars were restored. Temporary restorations were neither used before nor in between treatment sessions.

Before the cementation procedure, teeth were cleaned with pumice and water spray. Under moisture control (rubber-dam or cotton rolls), the restorations were adapted and cleaned. The adhesive surface area of the Lava Ultimate restorations and all old direct fillings remaining in the abutment teeth were air abraded (CoJet (30 µm), 3 M). The restorations received a silane treatment and an adhesive layer (ESPESIL/ Scotchbond Universal, both 3 M). Tooth substrates were etched (15 s, 37% H<sub>3</sub>PO<sub>4</sub>) and rinsed (10 s). Silane was applied on old restorations, the universal adhesive was spread evenly on the whole surface for 20 s, then polymerized for 15 s (Bluephase 16i, Ivoclar, Schaan, Liechtenstein). After applying a dual cure adhesive resin cement (RelyX Ultimate, 3 M) and removing any excess, light curing (20 s/restoration surface) was performed. Occlusion and articulation were adapted using fine-grit diamond burs and polishing rubbers (Fig. 1F).

In the second or an additional third session, direct multilayered RBC facial veneers (Filtek Supreme XTE, 3 M) were applied on all maxillary front teeth (Fig. 1G), on those mandibular front teeth where indirect restorations were placed lingual and, on some premolars, where it was necessary to satisfy cosmetic demand. There were no direct facial veneers applied on molars. After roughening the contact area to the Lava Ultimate restorations with a bur, air abrasion was performed using Cojet (3 M). Hence, silane and bonding (ESPESIL/ Scotchbond Universal, both 3 M) were applied as described above and direct composite veneers were placed using Filtek Supreme (3 M). Facial veneers were evaluated as

separate restorations on the same teeth.

#### 2.5. Follow-up

Patients participated in recall appointments at approximately one, three, and five-years (Fig. 1H). In between set recall appointments, patients could either visit their general dentists for regular check-ups or contact the university clinic in case of complaints. Data on all treatments performed by the general practitioners since intake was requested and all information on interventions recorded was noted until April 2023.

#### 2.6. Levels of failure and statistical analysis

As direct facial veneers were only placed on the vestibular side of front teeth and premolars, but not in molars, statistical analysis was carried out for indirect and direct restorations separately. Discolorations or roughness requiring refurbishment were not recorded as failures. For indirect restorations, three levels of failures were determined: (F1) severe deficiencies leading to restoration replacement or extraction of the tooth; (F2) localized deficiencies requiring local repair or re-cementation of a completely debonded restoration; (F3) small material chippings receiving polishing or no intervention at all [11,13]. Descriptive statistics were used to assess the clinical performance of the direct veneers. Survival was evaluated for up to 5.5 years for indirect restorations using lifetables and Kaplan-Meier graphs, distinguishing between failure categories and tooth type (front teeth, premolars, molars). Level three and level two failures were analyzed using Cox regression on the variables tooth type and location, age, gender, and VDO increase ( $p < 0.05$ ). For level one failures (F1), the number of failures (6) was too low to apply Cox regression.

### 3. Results

Twenty-two patients were recruited and restoratively treated between February 2014 and January 2018 (Fig. 2). Clinical follow-ups were carried out for 21 patients (aged  $40.4 \pm 10.7$  years at baseline; 3 female/18 male). One patient was unable to attend any recall appointments due to personal problems, which were not related to the treatment. In total, 200 direct veneers were applied on maxillary front teeth (120), on those mandibular front teeth where indirect restorations were placed lingual (55) and, on upper (22) and lower (3) premolars for aesthetic reasons. Furthermore, 568 indirect restorations on 158 molars, 163 premolars, and 247 front teeth were included in this prospective study (Table 1). Sadly, two patients died during the study (LU-06 5.1 years/ LU-09 5.7 years after placement of the first restoration).

The indirect restorations showed 96 failures up to 5.5 years (F1:6, F2:41, F3:49), including multiple failures on the same restorations (Table 1). All six severe deficiencies leading to replacement (F1) were recorded on premolars and occurred due to broken restorations and/or deficiencies of the underlying tooth substrate requiring restoration renewal. Most adhesive fractures required repair ( $n = 29/32$ ) and small chipping fractures could mostly be polished ( $n = 46/48$ ; Table 2). Caries was the reason for four repairs in three different patients. In four cases the reason for repair was not documented according to the general dentists' documentation. One tooth (second lower left molar, patient LU-16) needed endodontic treatment, resulting in an occlusal repair of the indirect restoration.

Kaplan-Meier graphs depict the survival probability for the indirect restorations in percent for different failure levels distinguished by tooth type up to 5.5 years (Fig. 3). Tooth type had an influence on the survival probability of indirect restorations in all failure categories ( $p < 0.05$ ). Survival concerning level two and three failures was higher for front teeth than for premolars, and higher for premolars than for molars (Table 3). Annual failure rates (AFRs) over 5.5. years consequently showed the reciprocal sequence. For shorter time intervals (0–1 y, 1–3 y, 3–5.5 y), AFRs constantly increased for level three failures in molars

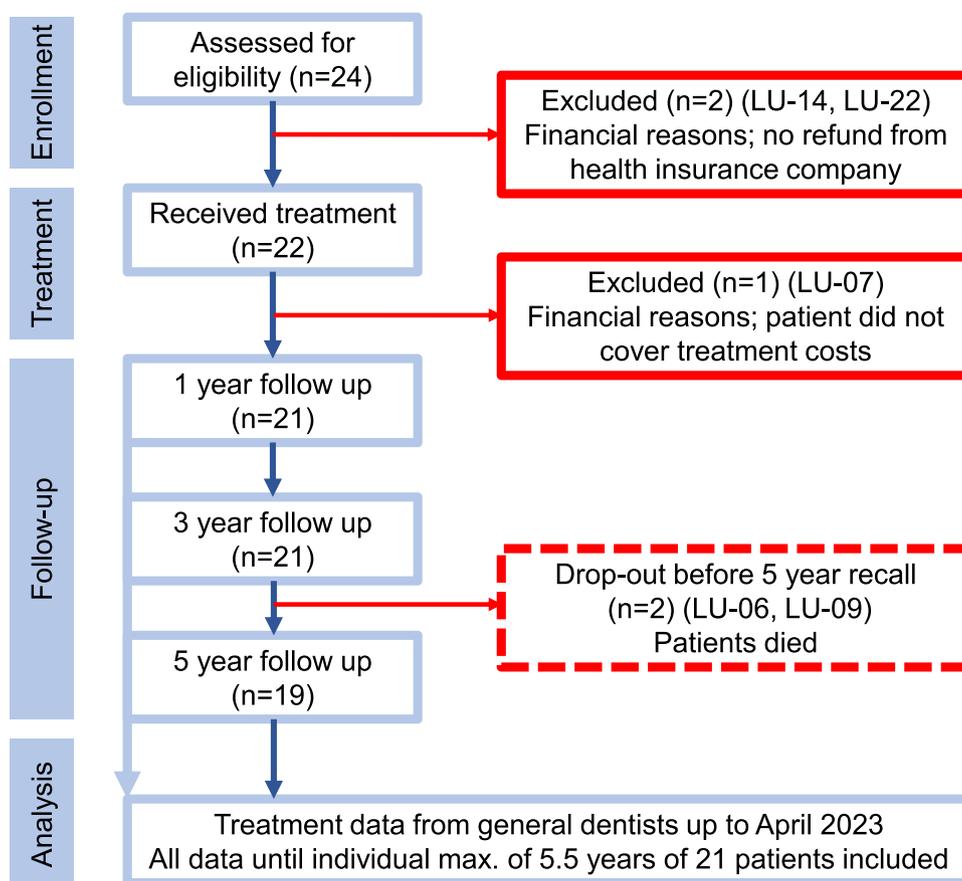


Fig. 2. Flowchart of patients regarding assessment, treatment, follow-up and analysis.

(2.5%, 5.4%, 8.1% respectively). For level three failures in premolars and front teeth, as well as for level two failures for all tooth types, AFRs rose from the 0–1y-interval to the 1–3 y interval and decreased again in the third interval from 3–5.5 years.

Level three and level two failures were analyzed using Cox regression. For level one failures (F1) the number of failures (six) was too low to apply Cox regression. The analysis was performed on the variables tooth type, age, gender, and increase of VDO. Molar tooth type had a statistically significant increased chance of failure compared with all other tooth types concerning F3 failures ( $p < 0.006$  for F3). For F2 failures, molars showed no significant difference to premolars ( $p = 0.106$ ) but still had a significantly increased chance of failure compared with front teeth ( $p = 0.002$ ). No other indication was found that neither the factors location (upper vs. lower jaw), age, gender nor VDO increase were likely to influence the chance of restoration failure ( $p > 0.05$ ; Table 4).

The chemical wear scores (CWS, range 0–3) and mechanical wear scores (MWS, range 0–2) were considered as explanatory variables in the Cox regression analysis, but no indication of increased chance of failure due to either score was found. As both variables violated the proportionality condition that Cox regression imposes, both were omitted from the analyses presented. Descriptively, three patients showed more failures than the rest: patient LU-03 showed 21 failures (F3 = 14, F2 = 7; MWS = 2, CWS = 0), patient LU-10 demonstrated 15 failures (F3 = 7, F2 = 8; MWS = 1, CWS = 1) and 14 failures were recorded for LU-08 (F3 = 4, F2 = 10; MWS = 1, CWS = 1). The other patients showed up to nine failures, with patient LU-02 (MWS = 0, CWS = 3) being the only one showing no failure at all. From the nine recorded severe failures (F1), four were found in patient LU-23 (MWS = 1, CWS = 3).

Of the direct veneer restorations, a total of 18 failures were recorded up to 5.5 years (F1:2, F2:9, F3:7). The two severe deficiencies (F1)

presented as one bulk fracture (LU-01, central lower left incisor) and one complete renewal of upper front teeth, as the patient was not satisfied with the esthetics of a repair procedure performed previously due to a partial fracture (LU-13, tooth central upper left incisor). Level 2 and 3 failures were rarely noticed by the patients and were mostly recognized during recalls. Those could either be easily repaired (F2, Fig. 4a-c) or refurbished (F3). All adhesive fractures ( $n = 6$ ) were repaired, and most of the chip fractures were only refurbished ( $n = 7/9$ , Table 2).

## 4. Discussion

### 4.1. Indirect restorations

The aim of this study was to assess the mid to long-term clinical performance of minimal-invasive CAD/CAM resin-based composite (RBC) restorations and direct RBC veneers in severe tooth wear patients by evaluating their survival up to 5.5-years. The survival probability after 5.5-years of indirect restorations on posterior teeth (M=molars, PM=premolars) were comparable to a group treated with direct RBC build-ups concerning catastrophic (F1 – indirect: 96.8%(PM), 100%(M) – direct 98.3%(PM+M)) and repairable (F1 +F2 – indirect: 91.7%(PM), 84.9%(M) – direct: 89.2%(PM+M)) failures. Small failures requiring refurbishment or polishing, occurred with a higher probability on indirect than on direct restorations on molars (F1 +F2 +F3 – indirect: 87.3%(PM), 70.7%(M) – direct 87.7%(PM+M)) [11]. Comparing the current dataset on anterior indirect restorations with the respective study showed better results for the indirect RBC materials (F1 – indirect: 100% – direct 97.2%, F1 +F2 – indirect: 98.4% – direct 91.4%, F1 +F2 +F3 – indirect: 97.1% – direct 89.3%) [11]. Oudkerk et al. [12] reported a survival (comparable to F1) of 100% and a success (comparable to F1 +F2 +F3) of 93.5% over two years following a

**Table 1**  
Overview over patient characteristics, wear scores, treatment specifics and clinical outcomes.

Patient-Nr.	Patient-ID	Patient age at baseline (years)	Gender	Mechanical Wear Score	Chemical Wear Score	Total number of teeth treated	Total number of restorations placed	Increase VDO at location of first molar [mm]	Failures direct veneer restorations (Filtek Supreme XTE)			Failures indirect restorations (Lava Ultimate)			Total number of failures Direct and indirect restorations
									F1 Replaced or lost	F2 Repaired	F3 Refurbished	F1 Replaced or lost	F2 Repaired	F3 Refurbished	
1	LU-01	66.6	male	2	0	25	40	2.9	1	1	0	0	0	3	5
2	LU-02	40.7	male	0	3	26	34	1.7	0	0	0	0	0	0	0
3	LU-03	40.2	male	2	0	27	33	2.3	0	0	0	0	7	14	21
4	LU-04	49.1	male	1	2	27	34	3.0	0	0	0	0	1	0	1
5	LU-05	47.5	male	2	1	28	40	3.0	0	1	0	0	3	1	5
6	LU-06	52.6	male	1	3	28	36	3.2	0	0	0	0	1	0	1
7	LU-08	29.4	male	1	1	28	40	2.8	0	4	0	0	6	4	14
8	LU-09	39.3	male	2	1	28	40	2.5	0	1	0	0	1	0	2
9	LU-10	43.4	female	1	1	28	40	3.3	0	0	2	0	8	5	15
10	LU-11	47.9	male	0	2	27	37	3.5	0	0	0	0	2	0	2
11	LU-12	23.0	male	1	3	28	40	1.2	0	0	0	1	2	1	4
12	LU-13	32.2	male	1	0	28	38	3.0	1	2	2	0	0	1	6
13	LU-15	29.5	female	1	2	28	40	3.5	0	0	1	0	0	2	3
14	LU-16	37.7	male	1	2	27	32	4.1	0	0	0	0	1	1	2
15	LU-17	31.5	female	2	1	28	42	1.9	0	0	0	0	2	1	3
16	LU-18	31.8	male	1	2	28	28	2.9	0	0	0	1	2	1	4
17	LU-19	40.9	male	0	2	28	36	2.9	0	0	0	0	0	5	5
18	LU-20	42.7	male	1	3	27	35	2.0	0	0	0	0	1	3	4
19	LU-21	41.3	male	0	2	26	32	2.8	0	0	2	0	3	4	9
20	LU-23	56.1	male	1	3	25	37	3.3	0	0	0	4	1	1	6
21	LU-24	25.5	male	1	3	28	34	3.4	0	0	0	0	0	2	2

**Table 2**

Overview of failure reasons recorded for different failure levels (F1-F3) for indirect and direct restorations.

		F1: Replaced or lost	F2: Repaired	F3: Refurbished
<b>Indirect restorations (n = 568)</b>	Complete debond	6	1	
	Adhesive fracture		29	3
	Chip fracture		2	46
	Caries		4	
	Endodontic Treatment Reason unknown		1	
	TOTAL	6	41	49
	<b>Direct veneer restorations (n = 200)</b>	Bulkfracture	1	
Adhesive fracture			6	
Chip fracture			2	7
Esthetics		1		
Reason unknown			1	
TOTAL		2	9	7

non-preparation treatment of full mouth severely worn dentition in a prospective clinical study using a polymer-infiltrated ceramic network CAD-CAM composite material. Torosyan et al. [7] performed a retrospective noninterventional study on different tooth-colored restorations. A six-year survival of 99% was presented on minimally invasive full-mouth rehabilitation, revealing no differences in survival between RBC or ceramic restorations [7]. Edelhoff et al. [14] presented a comparable survival of 100% in the 103 adhesively bonded lithium disilicate ceramic onlays with a mean thickness of one millimeter in load-bearing areas in seven patients after a mean observation period of 7.9 years.

Although a variety of different tooth-colored materials are able to apparently achieve high mid-term clinical survival and success, indirect RBC materials were chosen for the presented study group due to the superior mechanical properties achieved mainly by optimal extraoral polymerization processes [19]. Indirect RBC materials are claimed to have a higher wear resistance than direct RBC materials in laboratory wear testing [23], but further clinical studies for validation and comparison are required [19]. Although indirect RBC materials are not as brittle as ceramics, CAD-CAM processes might cause microcracks on the surface that cause minor defects under loading, which then require refurbishment. In the current study, fractures were the main reason for failure (32 adhesive fractures, 48 chip fractures) for indirect restorations, which is in accordance with the results of a five-year retrospective case series study, treating a comparable cohort of severe tooth wear patients [24]. Since no facebow was applied but only intraoral silicon stops and an intraoral scanner were used to determine the rehabilitated intercuspation, only static occlusal relationships were recorded before the manufacture of the indirect restorations. Although experienced practitioners thoroughly adjusted static and dynamic occlusion after restoration placement, adverse occlusal forces might have occurred in some areas, leading to early failures by fracture [25]. Furthermore, as the annual failure rates of molars concerning polishable failures increased over time, the wear mechanisms in the oral environment might accelerate degradation processes. Including annual failure rates (AFRs) of all failure levels and all tooth types, thereby covering all interventions made, the current findings (AFRs 0.0–8.09%) are in accordance with the results of the systematic review of Kassardijan et al. [18] on RBC restorations placed on worn occluding surfaces of front and posterior teeth, where annual intervention rates between 0.8% and 17.8% were reported. Although restorations need maintenance in form of smaller repairs or refurbishments, the main goal of protecting the remaining original tooth substrate can be achieved with this

conservative approach.

Molar teeth showed a statistically significant increased chance of failure compared with all other tooth types (for F3 failures), which has been previously reported for direct full coverage restorations in the posterior area [11,26]. For molars with only indirect restorations, no catastrophic failures were recorded. This is in accordance with other clinical studies of comparable mean observation times, using minimally invasive techniques with indirect, adhesively bonded, tooth-colored materials [7,12,14].

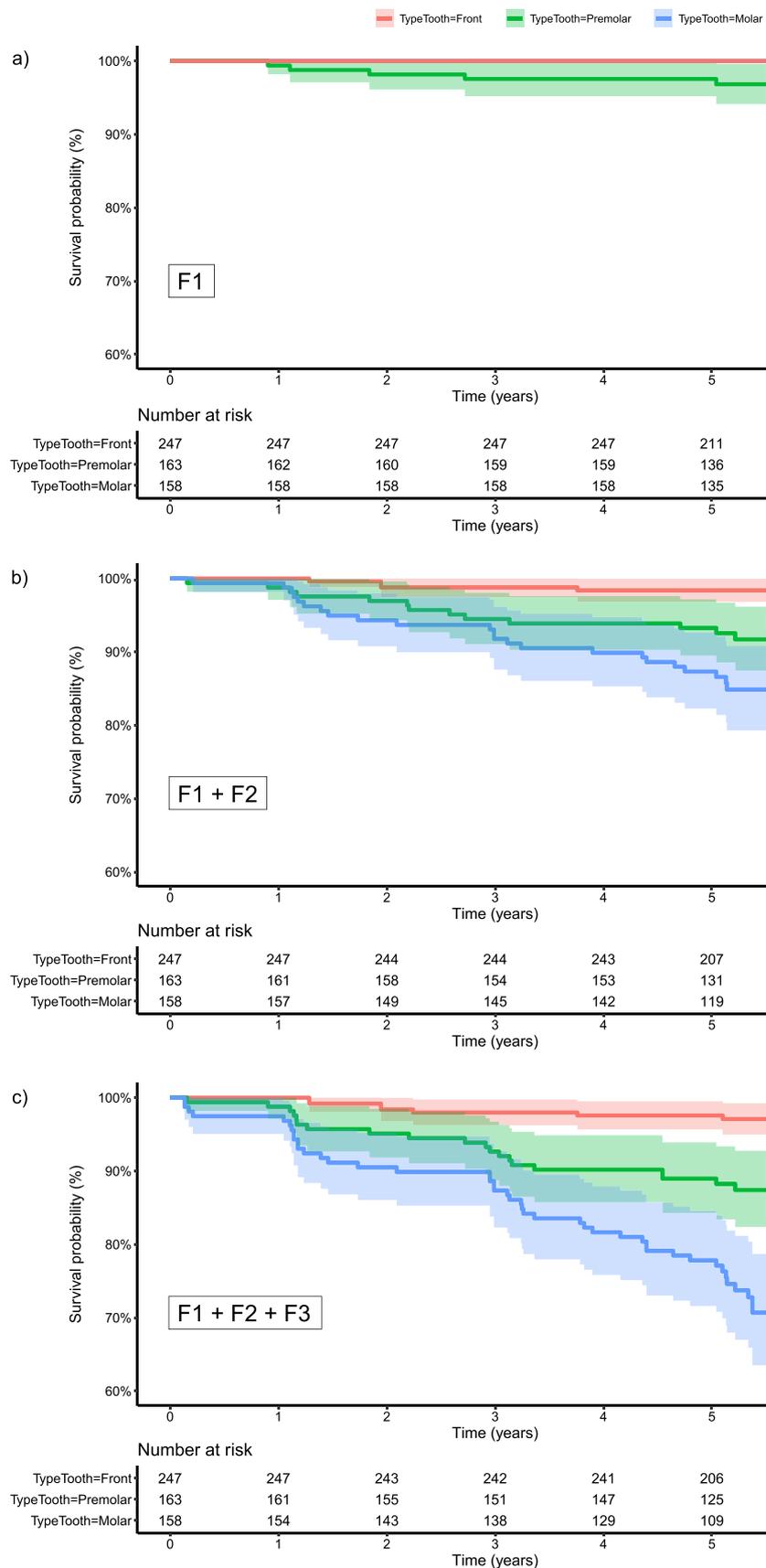
#### 4.2. Direct restorations

Additionally, to the indirect restorations, directly applied RBC facial veneers were descriptively evaluated as separate restorations with 18 failures being recorded up to 5.5 years. Fractures were also the main reasons for failure (15) for direct restorations, which was previously reported [27–29]. One reason for requiring the complete renewal of a facial veneer was that the patient was not satisfied with the esthetic appearance of the repair performed after a partial fracture. In comparison to studies on restorations in the posterior area, systematic reviews and selected cohort studies on front teeth restorations showed that failures due to esthetic complaints were reported more often in this area [27].

As all direct restorations evaluated in the current study were applied as buccal veneers, the interface to the indirect restoration placed beforehand might play a role concerning restoration survival. Staining, loss of luster, wear and loss of marginal adaptation were described as a progressive deterioration process at this incisal RBC-RBC interface over 36 months in situ [30]. As shown in Fig. 4, failures on direct restorations mostly started on the incisal edge, which could either be explained by these continuous deterioration processes or by the fact that the incisal edge is the only loaded area of a buccal veneer in regular occlusion. From the 15 recorded fractures only six occurred at the adhesive interface whilst nine were recorded as cohesive chipping fractures. As the facial veneers were mostly applied in a subsequent session to the insertion of the orally placed indirect restorations, the adhesive processes can be compared with a repair of an aged RBC restoration. Roughening the surfaces with intra-oral air-abrasion and subsequent silane application were used in the current study protocol, which was shown in literature to be able to improve bond strength [31], especially for Lava Ultimate restorations [32]. A recent randomized clinical trial on repaired posterior direct RBC restoration could not find significant improvement of the success of repair by adding silane and/or air abrasion pre-treatment [33]. However, the clinical observation period was limited to six months and failures might take longer to occur.

#### 4.3. Patient related factors

When reporting on full-mouth rehabilitations such as the current study, it should always be considered that one patient received multiple restorations, being related to the same possible patient-risk factors as age, gender, mechanical and erosive challenges applied, as well as caries risk. In the current study, three patients showed noticeably more failures than the rest (LU-03: 21 failures, LU-10: 15 failures, LU-08: 14 failures – all others ≤ 9 failures). Although neither the analysis of chemical (CWS) nor mechanical wear scores (MWS) showed any significant results, this may likely be due to the low power and it must be noted that for the three patients showing the majority of failures, low chemical scores were given. A recent analysis by Crins et al. [13] showed that the absence of chemical wear in patients at intake increased the risk for failing restorations, which is at least not contradictory to the outcome of the present study. In those studies, we used to compare our results to [7,12,14], the type of wear (CWS/MWS) was not assessed. Therefore, without information on patient factors and possible exclusion of severe bruxing patients in some studies, great care should be taken when interpreting differences between materials.



**Fig. 3.** Kaplan-Meier graphs including respective numbers at risk, showing the survival probability in percent (scale 60–100%) for different failure levels distinguished by tooth type up to 5.5 years (background colors presenting 95% confidence interval): front teeth = red, premolars = green, molars = blue; a) F1: severe deficiencies leading to restoration replacement or extraction of the tooth (blue line hidden behind red line); b) F2: localized deficiencies requiring local repair or re-cementation of a partially de-bonded restoration; c) F3: small material chippings receiving polishing or no intervention at all.

**Table 3**

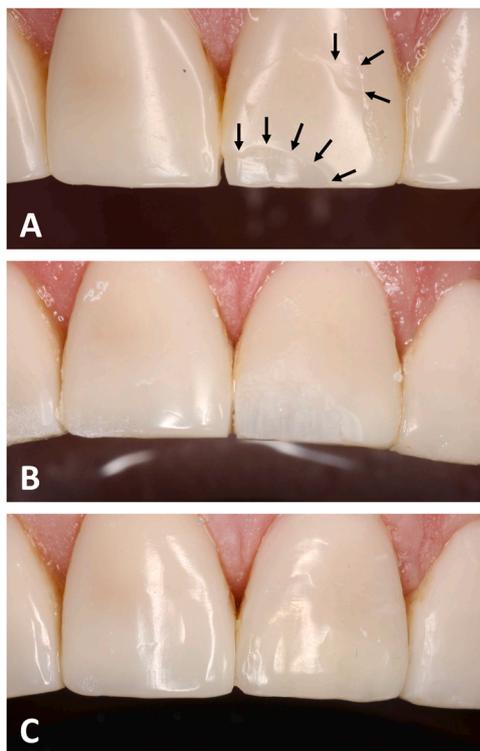
Survival and annual failure rates (AFRs) of indirect resin-based composite restorations (Lava Ultimate) shown for different failure levels (F1: severe deficiencies leading to restoration replacement or extraction of the tooth; F2: localized deficiencies requiring local repair or re-cementation of a partially de-bonded restoration; F3: small material chippings receiving polishing or no intervention at all), tooth types (front teeth, premolars, molars) and evaluation intervals (up to 5.5 years; y = year).

		Survival (%)			Annual Failure Rates (AFR, %)			
		up to 1 year	up to 3 years	up to 5.5 years	AFR (0-1 y)	AFR (1-3 y)	AFR (3-5.5 y)	AFR (0-5.5 y)
F1	Front teeth	100	100	100	0.00	0.00	0.00	0.00
	Premolars	99.4	97.5	96.8	0.60	0.96	0.29	0.59
	Molars	100	100	100	0.00	0.00	0.00	0.00
F1+F2	Front teeth	100	98.8	98.4	0.00	0.60	0.16	0.29
	Premolars	98.8	94.5	91.7	1.20	2.20	1.20	1.56
	Molars	99.4	91.8	84.9	0.60	3.90	3.08	2.93
F1+F2+F3	Front teeth	100	98	97.1	0.00	1.01	0.37	0.53
	Premolars	98.8	92.6	87.4	1.20	3.19	2.29	2.42
	Molars	97.5	87.3	70.7	2.50	5.38	8.09	6.11

**Table 4**

Results of Cox-regression analysis of indirect resin-based composite restorations (Lava Ultimate) shown for different failure levels (F2: localized deficiencies requiring local repair or re-cementation of a partially de-bonded restoration; F3: small material chippings receiving polishing or no intervention at all); analyzing influence of location (upper vs. lower jaw), tooth type (front tooth, premolar, molar), age [years], gender, and amount of increase of vertical dimension of occlusion (VDO) [mm] at  $p < 0.05$ .

	Level 2 failure (F2)			Level 3 failure (F3)		
	HR	95% CI	p	HR	95% CI	p
Upper vs Lower jaw	0.747	[0.374.1.492]	0.408	1.015	[0.568.1.815]	0.960
Front vs Molar	0.105	[0.025.0.437]	0.002	0.092	[0.037.0.226]	< 0.001
Premolar vs Molar	0.535	[0.251.1.142]	0.106	0.423	[0.228.0.783]	0.006
Age [yrs]	1.003	[0.953.1.055]	0.923	1.005	[0.973.1.039]	0.752
Male vs Female	0.689	[0.182.2.612]	0.584	0.754	[0.236.2.404]	0.633
VDO [mm]	0.893	[0.53.1.505]	0.671	0.977	[0.605.1.576]	0.924



**Fig. 4.** Clinical pictures upper central left incisor, patient LU-05, 1-year recall appointment: A) chipping fractures failure level 2 (black arrows indicating fracture lines); B) preparation for repair: situation after roughening and sandblasting; C) finished repair after polishing.

Considering the gained increase of vertical dimension of occlusion (VDO), LU-03 had a limited height increase of 2.3 mm at the location of the first molar, whereas LU-10 and LU-08 roughly reached the aspired 3 mm (3.3 mm and 2.8 mm, respectively). However, the VDO increase in the first molar region of LU-02, the only patient experiencing no failure, was limited to 1.7 mm. Statistically, no correlation between the amount of VDO increase in the current study and a higher risk of failure was found. Comparable with the current results, polymer-infiltrated ceramic network CAD-CAM composite materials in very low thicknesses ( $0.55 \pm 0.21$  mm) reported promising results after two years with a restoration survival of 100% and a success of 93.5%, comparable with the survival probabilities up to three years in the current study (F1  $\approx$  survival 97.5–100%, F1 + F2 + F3  $\approx$  success 87.3–98%) [12]. The adhesive protocol might have supported the current outcome, as it was shown in laboratory tests that load-bearing capacities comparable with natural tooth substrate of ultra-thin ( $\sim 0.5$  mm) Lava Ultimate restorations could be achieved when those were adhesively luted to enamel [34]. In clinical studies on full mouth rehabilitation, only rarely the VDO increase per patient is given but rather a range for the whole patient cohort. Nevertheless, the aspired VDO increase of 3 mm (range 1.2 - 4.1 mm) in the current study is comparable to investigations on the rehabilitation of severely worn dentitions with direct RBC materials. In a prospective study on 98 posterior occlusal restorations in seven patients with a VDO increase of 2 - 4 mm, annual failure rates of 3.48% for anatomical form and 3.71% for marginal integrity were reported over an observation time of  $40.8 \pm 7.2$  months [35]. In another retrospective analysis, eight patients with severely worn dentitions received 105 nano-filled direct RBC restorations on premolars and molars with a VDO increase of 2 - 3 mm. Twenty-three of these restorations showed repairable defects up to 5.2 years, none had to be replaced [36]. Although all posterior restorations were analyzed together, the resulting overall success rate of 78.1% up to 5.2 years is in the range of the current findings for premolars (F1 + F2 + F3 = 87.4%) and molars (F1 + F2 + F3 = 70.7%).

At intake, caries risk was not specifically assessed for patients included in the study, although patients that presented with deep caries lesions were excluded. However, and although it is known to be a possible risk-factor for restoration failure on a patient-level [8], caries was the reason for only four repairs in three different patients (max. two/patient) concerning indirect restorations. As the main reasons for failure in the present study were all related to fracture, it shows that the patient group was at high risk for fracture, which is clearly related to their condition of having severe tooth wear, while their caries risk was low.

#### 4.4. Failure levels and clinical relevance

In the current study, no differentiation between ‘survival’ and ‘success’ took place, but the survival was evaluated on different failure levels (F1: severe deficiencies leading to restoration replacement or extraction of the tooth; F2: localized deficiencies requiring local repair or re-cementation of a completely debonded restoration; F3: small material chippings receiving polishing or no intervention at all). As such, using the definition of Survival and Success according to Anusavice [37] in our study F1 could be named ‘survival’ and F1 +F2+F3 could be named ‘success’.

An observation period of more than 5-years was evaluated according to the recommendations in the latest guidelines for evaluating indirect dental restorations [38]. As the USPHS and FDI criteria were mainly developed for rating intracoronal restorations (Class I/II cavities), the adapted concept to the recommended three grade system recommended for practice-based studies (sufficient/acceptable = score 1–3, insufficient/inacceptable but repair possible = score 4, insufficient/inacceptable but repair not possible/reasonable = score 5) was used. Following the conservative approach of the Radboud Tooth Wear Project (RTWP), interventions should not be performed due to clinically functional imperfections [39], but only due to real deficiencies like cavitated caries lesions, (bulk-) fractures, or patients’ dissatisfaction [8]. A statistically significant improvement in the oral health-related quality of life of patients treated in scope of the RTWP supports this treatment concept in addition to the presented results in this study [40]. Of course, and especially in these high-risk patients, a long-term treatment plan might require constant maintenance [27], or re-treatment to re-establish a proper VDO and overcome esthetic impairments. Although the survival of the restoration is the main outcome investigated, the preservation of the already worn dentition with functional and esthetical rehabilitation is the main aim. Even if the restoration is worn down or fractured, a comparable treatment can be performed again without further damaging the tooth structure.

#### 5. Conclusion

Minimal-invasive CAD/CAM resin-based composite restorations showed a clinical survival of 96.8–100% and clinical success of 70.7–97.1% after up to 5.5 years for restorative rehabilitation of severely worn dentitions. Restorations on molars showed a higher failure probability than those on premolars and front teeth.

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