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Ex-vivo comparison between different protocols used for single-tooth adhesive restorations: digital versus traditional techniques

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Anno Accademico 2017/2018

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INTRODUCTION

Technologies are rapidly evolving, changing the way to treat and to communicate with patients. Digital in particular is giving clinicians new restorative opportunities such as aesthetical planning and Computer Assisted Design/Manufacturing [1,2]. Since 1970s, with Duret and Preston's work [3], CAD/CAM development has been based around three elements: data acquisition (optical impression), CAD processing (software and hardware) and manufacturing (milling machines, rapid prototyping) with the aim of making the process easier, faster, cheaper and more predictable. Nowadays for what concerns optical impression, LED sources (for intraoral scanners) and projectors (for extraoral scanners) combined with elaborated algorithms are used in order to obtain high-quality multiple 3D data sets every second (video recording), even in color mode and without superficial coating [4]. The exponential hardware and software improvements resulted in major overall advantages allowing to project and customize nearly any kind of restoration, even chairside [5].

Chairside systems allow the clinicians to independently design and mill restorations in a single appointment, with benefits in terms of materials, aesthetics, costs and patient discomfort [6]. In these terms, manufacturing has been improved as well, with highly compact and performing milling machines and new additive technologies such as selective laser sintering and stereolithography (SLA) [7,8].

Using these technologies, a single-tooth indirect adhesive restoration can be performed in three different ways: traditional workflow, extraoral digitalization (from impression or cast) and intraoral digitalization. STL files can also be used to print 3D casts (3DC), which are useful for materials characterization and to check contact points or occlusion. At present day, traditional workflow is still the most used, since most of these restorations are made with composite, which can guarantee easy management, fair aesthetical results and good long-term clinical performances [9,10,11,12]. Beside, digital protocols are opening huge opportunities with chairside procedures and machinable composite materials [13].

Conventional impressions (CI) and casts (CC) can today rely on modern materials with high performances when stored and used correctly [14,15,16,17]. PVS and conventional type IV gypsum in particular, showed great accuracy and precision [18,19,20]. However, final accuracy of casts always depends on the impression technique other than the materials themselves [21]. Moreover traditional technique has many disadvantages: high risk of distortions and dimensional changes due to the numerous steps (expansion or shrinkage), storage difficulty (lot of space required and risk of damage over time), patient's discomfort and difficulties related to multiple pour cast [22,23,24].

Extraoral impressions and gypsum casts scans (EOIS/EOCS) can add a digitalization error to the traditional procedure, but they allow usage of machinable materials [25]. Intraoral scans (IOS) have no chemical reactions involved, no storage or recovery problems and they provide time and passages reduction (no tray selection, wait time, cast setting time, disinfection, transport) with real-time evaluation in terms of thickness, undercuts and margins [26]. Powder necessity is disappearing with new systems, as well as the discomfort caused by intraoral cameras due to miniaturization. Persisting disadvantages of IOS are nowadays still related to precision and accuracy, affected by patient's movements, saliva and blood[25] , especially in full arch scans when lots of images have to be stitched together [27]. This last fact is confirmed by higher inaccuracies of IOS, compared to traditional workflows, for full arch impressions [28,29,30]. Moreover learning curve, high purchasing and managing costs are limiting the use of this technology [31]. Comparing digital and conventional workflows in terms of fit, both procedures achieved clinically acceptable results for single crowns and short fixed prosthesis [25,32]. Indirect restoration's fit, which is closely related to trueness and accuracy of impression and cast techniques, has to be considered a key factor for long-term prognosis of a restoration, since a defect can result in decreased mechanical properties, increased plaque accumulation and, consequently, augmented risk of caries and periodontal disease [33,34,35]. Aside fit analysis, trueness of digital scans has been researched through surface deviation analysis using superimposition on a reference model with "best fit" algorithms [36], concluding that accuracy varies between different intraoral scanners and conventional impressions, but deviations are within a similar magnitude for up to ten units even in vivo [37].

Concerning rapid prototyping technology, 3DC showed good performances in literature [38,39]: a recent review stated that it helps saving time with high level of accuracy, reproducibility and precision [7,40]. However, other studies reported superior accuracy and reproducibility of CC for complete arch, despite not in the area of a single-tooth crown preparation [36,41]. Therefore it must be considered that different printing techniques, systems and polymers will result in a very different quality of final casts [42].

Despite the great evidence regarding CAD/CAM ceramic crowns, there is lack of studies with comparative analysis between traditional and digital chairside techniques for the manufacturing of single tooth adhesive restorations (inlay, onlay, overlay) and their fit on CC and 3DC models. First of all, there are no available data concerning geometry of these preparations, which might be more or less suitable for digital procedures, compared to traditional crowns' geometry [43]. Secondly modern chairside materials, such as reinforced composites, have little evidence compared to traditional ceramics restorations. Lastly, most of the studies are in vitro under ideal circumstances, and little evidence with ex-vivo or in-vivo data is available.

AIM OF THE STUDY

Thus, the aim of the present ex-vivo study was to analyze trueness of digital workflow in generating casts (digital IOS cast and 3DC) compared to traditional protocol (CC) for the realization of indirect adhesive chairside restorations and then to evaluate these restoration's fit on 3DC and CC. The initial null hypotheses are that (1) there is no difference between different techniques (3DC, CC and IOS) and (2) there is no fit discrepancy of chairside restoration on 3DC and CC.

MATERIALS AND METHODS

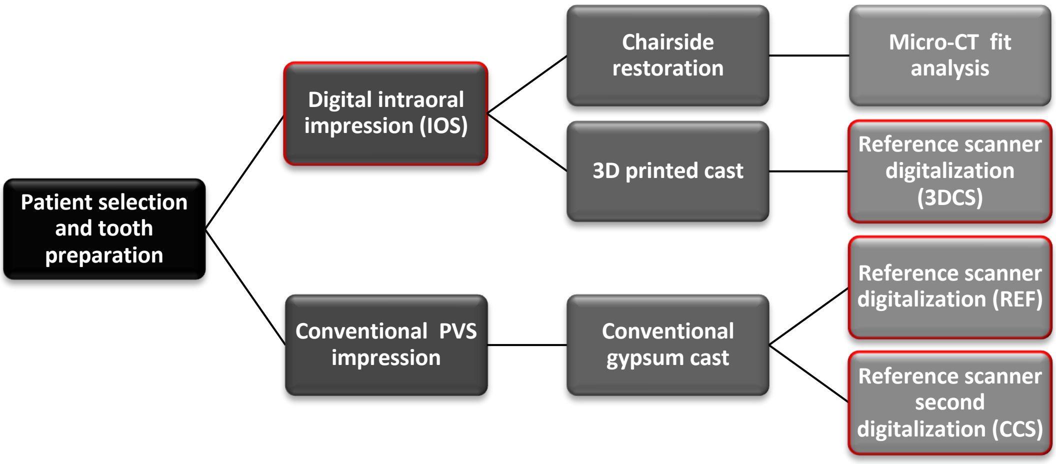


Figure 1. Summary of the study's structure, with highlights on passages where STL files were obtained.

Step 1 - Patients' selection and tooth preparation

Twenty patients afferent to Department of Cariology and Operative Dentistry (Dental School Lingotto, University of Turin) were recruited for this ex-vivo study. Selected patients needed indirect adhesive restorations on devitalized teeth due to the presence of carious lesions, coronal fractures or inadequate old restorations. Diagnosis was made by intraoral examination and four x-rays bitewings. Inclusion criteria were the followings: accepted informed consent, necessity of maximum two indirect restorations, occlusal stability, age between 18-65years, good general health conditions and good oral hygiene (FMPS<20%). Scaling was performed, if needed, in order to obtain healthy marginal tissues for the preparation. Exclusion criteria were the followings: impossibility of adequate field isolation, known allergies to one or more used materials, periodontal problems (advanced periodontitis, tooth mobility degree higher than 1, FMPS>20%), severe occlusion problems, undergoing orthodontic treatment, presence of TMD, reduction of DVO, absence of antagonistic element.

Preparation was performed by a single expert clinician with a standardized procedure: local anesthesia, rubber dam placement (Nic-tone, Dental Trey) to achieve full isolation, old restoration removal and hard tissues detersion, marginal cavity finishing in order to remove unsustained enamel and residual walls evaluation. Thin and cracked walls were removed and covered following a "minimally invasive" protocol, in order to preserve tooth sound structure as much as possible. After that, adhesive system was applied (Clearfil SE Bond 2, Kuraray) following manufacturer instructions. Buildup was performed with composite (Filtek Bulk Fill, 3M) with a traditional incremental layering technique to minimize polymerization stress on residual walls. Preparation was then carried out with uniform reduction according to material's manufacturer, with a minimum thickness of 1.5mm. Bur finishing and polishing of the surfaces were then performed in order to obtain smooth corners.

Step 2 – Impressions

Impressions were taken after rubber dam removal. First of all, on every patient an IOS by a trained operator, using Omnicam (CEREC, Dentsply Sirona), was performed following producer's guidelines: no direct light was applied and surfaces were dried as much as possible before and during the operation [44]. All the surfaces (oral, occlusal, vestibular) of the whole quadrant were scanned and digital occlusion was taken with vestibular intercuspidation recording. A standardized scanning time (45s) was employed for the preparation, in order to collect equal data volumes for the analysis. After that, a CI with a polysiloxane material (Express putty regular, ESPE, 3M and Express light regular ESPE, 3M) was taken following manufacturer's instruction. A single phase, bi-component technique (putty plus light) with flexible dual arch tray (Triple Tray, Premier Dental) was used after a clinical try-in of the tray itself.

Step 3 – Casts and STL management

IOS were immediately exported in STL format, while CI were sent to laboratory. After proper disinfection and setting time of 24-36h, CI were poured with scannable type IV gypsum (Uni-base 300, Dentona AG) and after 96hours, to wait until the expansion was complete [45], the CC so obtained were scanned twice each with reference laboratory scanner (Sinergia Scan, Nobil-Metal) after the calibration of the scanner itself. A reference STL file (REF) and a second STL file to test system accuracy (CC scan, CCS) were obtained. STL were managed with Optical RevEng Dental 2.0 (Open Technologies) to obtain the highest quality possible. 3DC were obtained printing the preparation plus 1mm surrounding area with multijet printing technology (MJP 2500 Plus, 3D Systems), after cropping STL from IOS, with a resolution of 800 x 900 x 790 DPI and 32 micron layers. 3D sprint software was used to manage files, and a dental resin material (Visijet M2R-TN, 3DZ System) was employed. 3DC were digitalized again by the same reference laboratory scanner and software to obtain STL files (3DC scan, 3DCS).

Step 4a- Surface deviation evaluation

In this ex-vivo study, surface trueness was defined according to ISO 5725–1 as "the closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted reference value". Four STL files (REF, IOS, CCS, 3DCS) for each patient were imported into Geomagic software at the same time (Geomagic Qualify 12, 3D Systems), aligned and manually trimmed together along the prepared tooth margins, to make the superimposition more precise: only this area was considered in the analysis. Trimmed files were then aligned again with another Geomagic software (Geomagic Control X 2017, 3D Systems) using "enhance alignment accuracy with feature recognition" and then "best fit algorithm" with the following parameters: sampling ratio 100%, no max.interation. REF was set as reference model for all superimpositions in order to evaluate trueness of new techniques (IOS and 3DCS) compared to conventional one (CCS) [37,29,46,47]. A color-coded 3D deviation map was generated and measurements of average 3D deviation were collected for each superimposition.

Step 4b –Fit evaluation

A novel 3D evaluation method was applied for this analysis. CAD projects made on CEREC SW 4.5.2 (Cerec, Dentsply Sirona) were milled twice each, after calibration of the machine itself (Cerec MC XL chairside system), using "fast" mode and Cerasmart (GC) as material. A 120μm digital spacing in the axial and occlusal area only was applied. After refinishing and polishing, restorations were cemented on CC and 3DC with radiopaque flow (Herculite XRV Ultra Flow, Kerr). Polishing was performed again to eliminate flow excesses, then the samples were scanned with micro-CT (Skyscan 1172, Bruker) to evaluate fit, with setting parameters for high resolution scans: voltage = 100kV, current = 100μa, source to object distance = 220mm, pixel binning = 292, total scan duration = 40min, aluminum and copper (Al+Cu) filter, 15μm pixels and 0.5 rotation degree. NRecon was used to reconstruct specimens to obtain Dicom files, with the same Hu parameters for pairs of CC and 3DC. Thresholding was performed automatically with the range of Hu values corresponding to flow, in order to obtain two comparable STL masks of it (Mimics Medical 20.0, Materialise). The so obtained files were imported into Geomagic Qualify, trimmed to remove noise and then exported in Geomagic Control X. A 3D thickness analysis was performed using default settings on every single sample without superimposition. Measurements of average 3D thicknesses were collected. Geomagic procedure was repeated twice for each mask: the first time performing the analysis on the whole volume (global fit), the second one performing it only on marginal area (marginal fit).

Step 5 – Statistical analysis

Data were statistically analyzed with t-test of Student in order to investigate differences between the three tested groups (CCS, IOS, 3DCS). The same test was performed for micro-CT analysis. Data significance was set for $p<0.05$. All statistical analyses were performed using Stata 12 (StataCorp, College Station, Texas, USA).

RESULTS

Mean data (± standard deviation) of superficial average deviation, expressed in µm, are reported in Table 1 and graphically summarized in Figure 2.

CCS (n=20)	-1,705 ± 3,941
IOS (n=20)	12,940 ± 12,240
3DCS (n=20)	21,920 ± 10,011

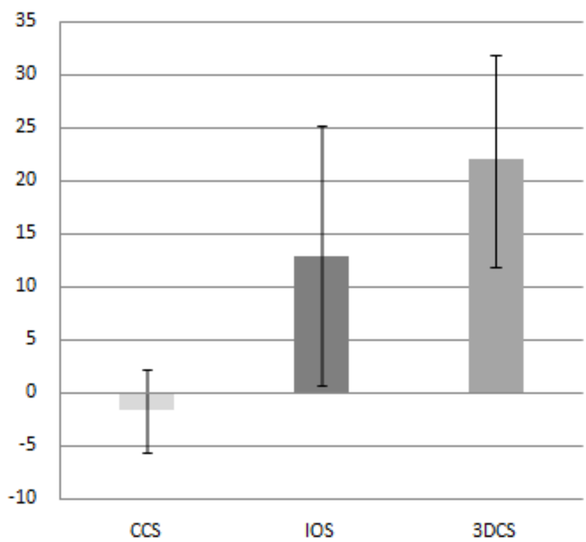


Table 1 (left). Average deviation (± standard deviation) for each group expressed in µm, with approximation at third decimal. Figure 2 (right). Graphical representation of Table 1.

Results of t-Student test showed that IOS and 3DCS significantly differed from CCS. Moreover, 3DCS was significantly different from IOS, but had an average deviation significantly inferior then the one obtained from CCS compared to IOS. A representative scheme of the obtained superimpositions with the procedure is reported in Figure 3.

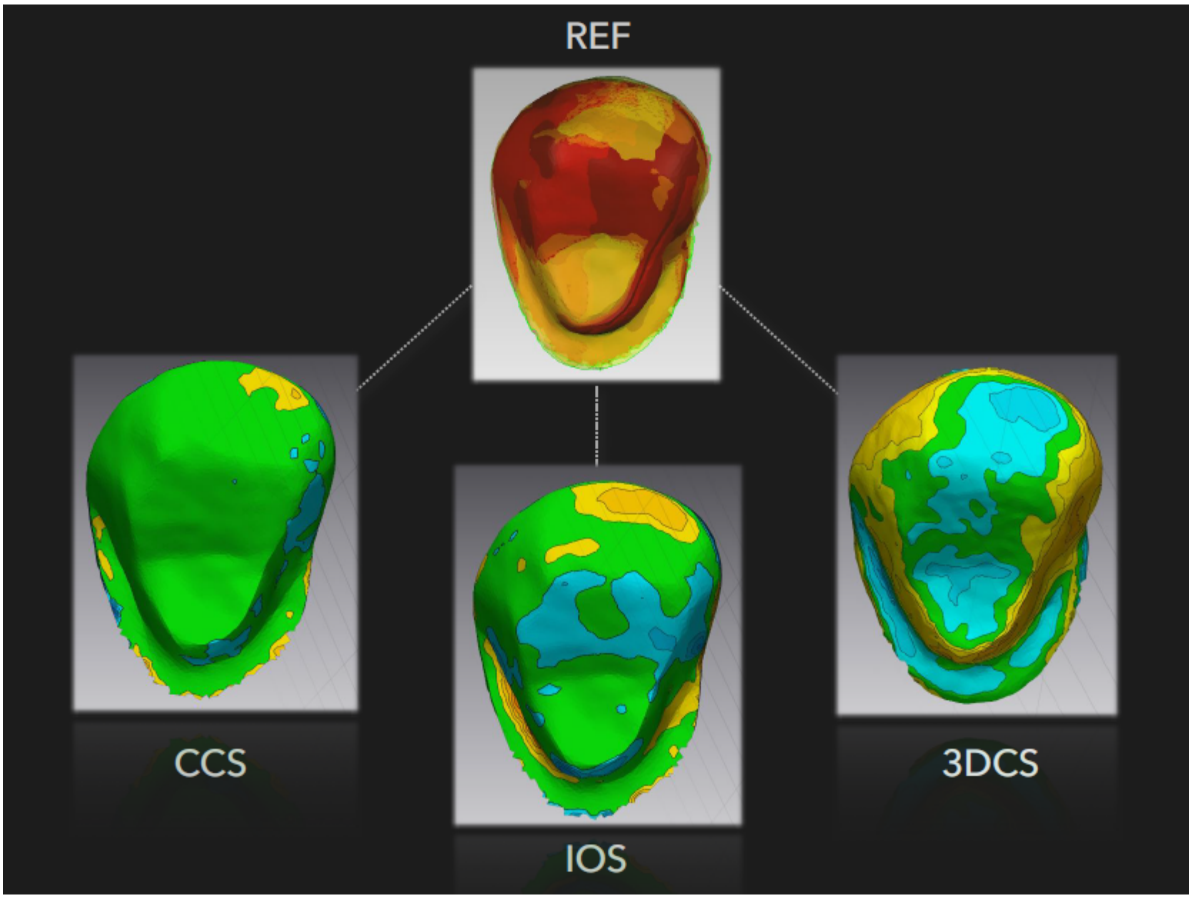


Figure 3. REF file aligned with CCS, IOS and 3DCS and relative obtained 3D deviation. Color bar was set as follows to maximize the value of graphical representation: minimum and maximum (blue and red) ±100μm, tolerance (green) ±10μm.

2. Micro-CT analysis

Mean data (± standard deviation) of average thickness, expressed in μm, are reported in Table 2 and graphically summarized in Figure 4.

CCS global fit (n=10)	212,31 ± 28,35
3DCS global fit (n=10)	144,50 ± 24,95
CCS marginal fit (n=10)	135,78 ± 30,85
3DCS marginal fit (n=10)	77,63 ± 22,24

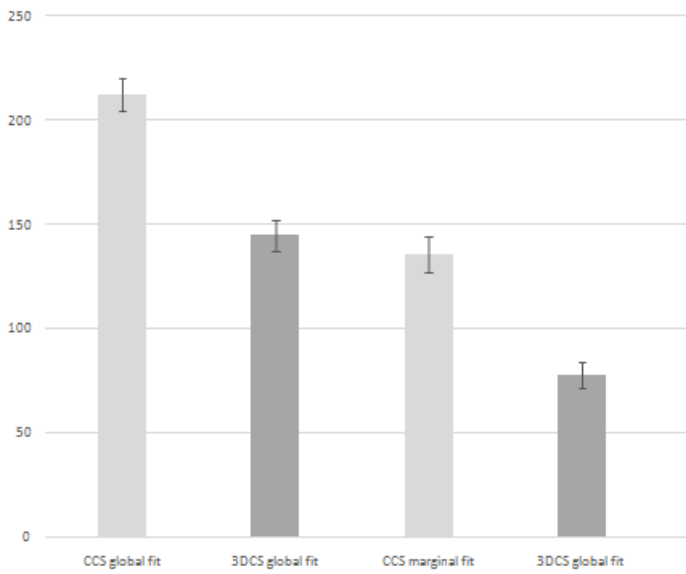
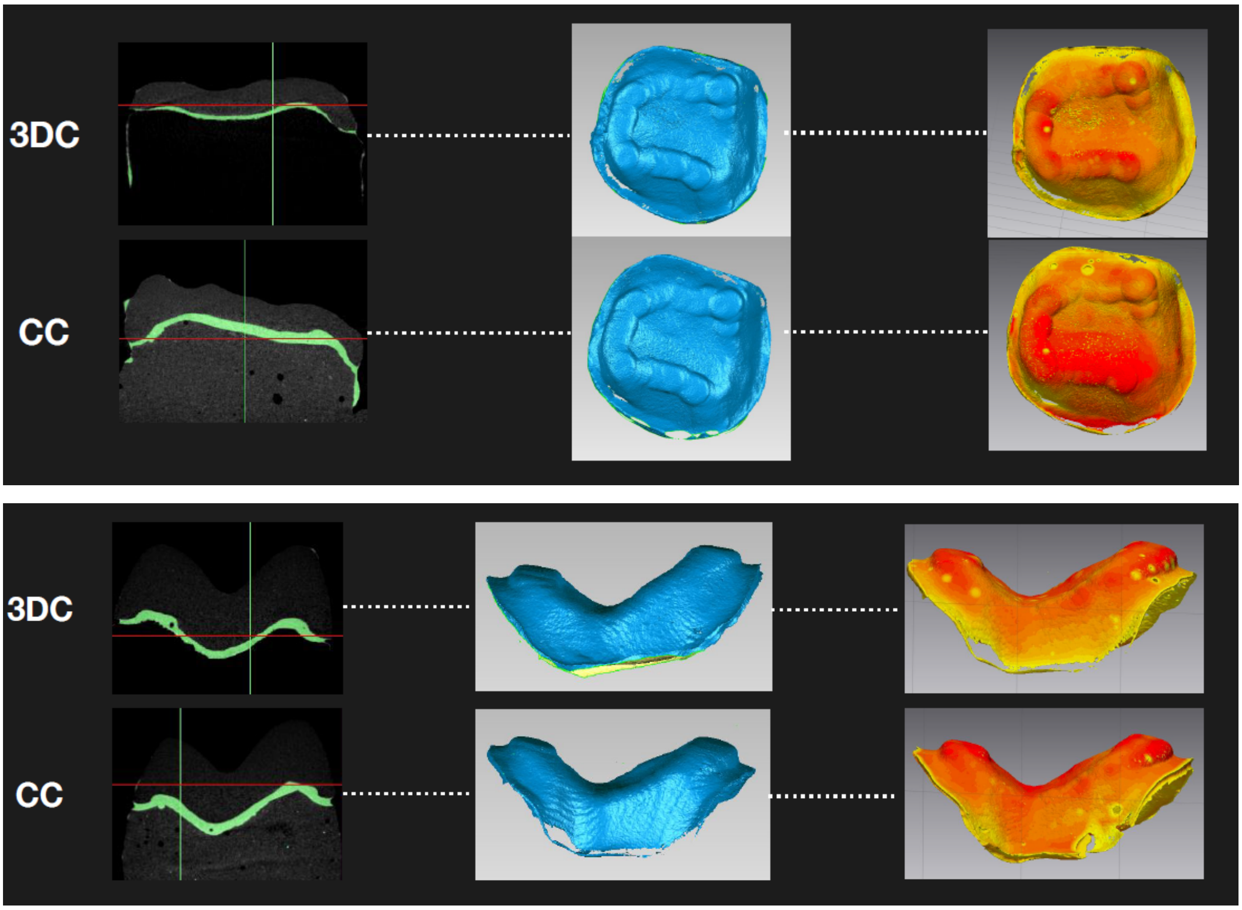


Table 2 (left). Mean 3D average thickness (± standard deviation) for each group expressed in μm, with approximation at second decimal. Figure 4 (right). Graphical representation of table 2.

Results showed significant differences between the two groups: for both global and marginal fit 3DC showed better adaptation compared to CC. A representative flowchart of the procedure, from thresholding to 3D thickness analysis, is reported in Figures 5 and 6.



Figures 5 and 6. Examples of analysis from thresholding to 3D thickness. Color bar was set as follows to maximize the value of graphical representation: maximum (red) 320μm, no tolerance.

DISCUSSION

Based on the obtained results, the first null hypothesis was rejected, since significant difference was found between tested casts.

Geomagic software has been widely use in literature to compare surfaces, and can consequently be considered a consolidated method of analysis [41,46,48,47]. The use of extraoral scanners as reference has been described as suitable for evaluating tooth preparation [49,50,51], however, in the present ex-vivo study, first CC scan (REF) was set as reference for all superimpositions since it was not possible to scan the patient's prepared tooth.

CCS differences from tested IOS could be related to Omnicam trueness: a discrepancy range of 12.94 ± 12.24μm was found in the present study. A similar value was reported by Güth et al. [27]: in their in vitro superimposition study an average deviation of 31μm from reference model was found for Omnicam IOS, while indirect digitalization reported a 19μm average deviation. Hack et al. showed even higher trueness deviation (45.2±17.1µm) when evaluating a single tooth scan with Omnicam [52] and similar conclusions were drawn by Renne et al. for what concerns sextant impressions [53]. However, it cannot be excluded that measured deviation was caused by impression's distortion or gypsum expansion. Employed traditional impression technique and material were selected basing the choice on what literature reports to be one of the most precise and common procedure for single tooth restorations [54,55,56,57,58,59]. According to Hamalian et al.[18], polyvinyl siloxane (PVS) was able to reproduce details from 1-2µm (for light viscosity) to 25µm (for putty viscosity), with 99% elastic recovery, high dimensional stability within 7-14days, moderate hydrophilicity, flowability range of 20-70µm, good flexibility and high tear strengths. The same can be stated for gypsum choice [60,61]: type IV gypsum casts, according to Potran et al., showed a trueness value ranging from -15µm to 24µm, and angular divergence from -0.09° to 0.18° [19], while according to Rudolph et al. the trueness range was between +10.9/-10.0 µm (SD 2.8/2.3) and +16.5/-23.5 µm (SD 11.8/18.8) [20]. Considering that impression deviation has to be added to gypsum deviation, this phenomenon could explain the discrepancies between IOS and CCS obtained in the present study.

CCS differed even more from 3DCS according to t-values: this could be associated to deviations' pile up during digital procedures, leading to an augmented difference [49]. A deviation range of 21.92 ± 10.01µm was found in the present study. A previous in vitro study [41], using superimposition, showed that CC have statistically superior accuracy and reproducibility for complete arch (CC 11±3µm in accuracy and 54±6µm in reproducibility versus 3DC 27±7µm and 91±10µm). However, in the area of a single-tooth crown preparation, comparable results to the present study were reported, with no statistically significant difference between the two models: for finish line area 3DC 10±0µm compared to CC 12±4µm, for the internal area CC 16±3µm compared to 3DC 21±4µm. Another study by Al-Imam et al., however, affirmed that CC had higher accuracy within the range of ±50µm [36], but the technology they used (SLA) is less-performing compared to multijet one used in the present study [38].

3DCS versus IOS results, on the other hand, could be explained considering that manufacturing a CAD file with any procedure brings to an inevitable, even if minimal, distortion. Moreover, additive technology is still under development and has highly different reported results, depending on several variables that are yet to be investigated [42,36,62]. Another important observation is that 3DCS appeared to have a lower level of deviation from IOS compared to the deviation of CCS from IOS itself, so it could be supposed that 3DC could be more accurate for chairside restorations' fit evaluation compared to CC.

Regarding interfacial adaptation analysis, the obtained results brought to reject the second null hypothesis, since a statistically significant difference between the two tested groups was found.

Micro-CT has been lately used in literature thanks to its high resolution and accuracy, and it has been selected for this study since it can provide an internal, non-destructive analysis of the samples compared to traditional methods (probing, direct viewing, cross sectioning techniques, clinical scores, replica method, photographs) [63,64,65,66,67,68,69,70,71,72,73,74]. Unfortunately, previous micro-CT studies could have some criticisms, since analysis was always performed with linear measurements on 2D images. Consequently, only few points could be measured, it was sometimes hard to have a repeatable reference and, lastly, operator played a big role in the selection of slices and starting/ending points of measurement. The present study aimed to reduce those biases, introducing automatic software thresholding combined with 3D analysis. A highly radiopaque flow was selected in order to perform a fast, precise and repeatable thresholding without any operator-dependent modifications. This composite material sometimes produced bubbles in the interface, but this deficiency could be considered surpassed by the huge number of points analyzed by the software.

The 3D analysis on micro-CT showed that 3DC had better marginal and internal fit values. This could be explained by the fact that the restorations were created on the same STL (IOS) from which 3DC were printed: any kind of deviation introduced in IOS would this way result in an analogue deviation in both restorations and 3DC. This reasoning led to the conclusion that, in a chairside protocol, considering a clinically acceptable IOS, 3DC was better to evaluate marginal and overall fit of restorations compared to CC, also in accordance with 3D surface deviation analysis performed in this study.

Besides, overall fit analysis appeared to show high gap values: this was not related to chairside system precision, but to the high-thickness digital spacing (120µm) that was intentionally applied in CAM phase. This was supported by the fact that in marginal area, where no spacing was applied, fit values were comparable to other studies concerning chairside CAD/CAM restorations [75,76]. According to McLean and von Fraunhofer [77], a clinically acceptable marginal gap around 60-120µm, was achieved only on 3DC. A meta-analysis by Chochlidakis[78], reported that full digital workflow led to better marginal adaptation then SLA dies: this evidence could lead to the conclusion that it’s easier, faster and more predictable, once STL file is obtained, to mill directly the restoration instead of printing the file and then perform a traditional procedure. However, a physical model is sometimes needed for pre-clinical evaluation: a multijet printed model could perform better than SLA and CC in these cases, according to the present study.

A recent meta-analysis showed that mean marginal gap for single-unit complete-coverage ceramic crowns was 63.3µm in vitro and 56.1µm in vivo with digital procedures, while 58.9µm in vitro and 79.2µm in vivo for conventional workflow [79]. Even if Tsirogiannis et al. concluded that there is no significant difference between impression's techniques, digital workflow seems to perform slightly better in vivo rather than in vitro. If full digital workflow, and therefore IOS, will be ever confirmed to be better in "in vivo" conditions, based on present study's obtained results, multijet printed casts could achieve higher trueness value, with tooth as reference, compared to CC and therefore become the "gold standard" for physical models. A 2017 systematic review on this topic conducted by Joda et al. [80], highlighted that, due to the lack of evidence, any conclusion regarding the full digital workflow could not be taken yet.

An intrinsic limitation of the present study was the impossibility of having tooth as reference, in order to compare it with all groups. An improvement could be introduced in future studies by using resin cast models, according to recent studies that report these materials to perform better compared to conventional type IV gypsum casts [81]. Errors regarding micro-CT analysis could have been introduced by imprecision of the milling procedure during the manufacturing of the same restoration's copies. However, this was unlikely to be real since all results were in accordance between each other.

CONCLUSIONS

Within the limitation of this study, it can be concluded that:

- IOS significantly differs from CC, but in a reduced range of microns.
- 3DC and CC have statistically significant differences between each other.
- 3DC have less deviation from IOS compared to CC using this protocol.
- Using this protocol, 3DC appears to be better in terms of overall and marginal fit, compared to CC, for the preclinical evaluation of chairside restorations.
- Composite chairside adhesive restorations show results of marginal fit comparable to values presented in literature for ceramic crowns.

Further in-vivo or ex-vivo studies are needed to confirm what previously reported.

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ACKNOWLEDGEMENTS

Dopo circa un'ora di riflessione davanti al foglio bianco, posso con certezza affermare che i ringraziamenti sono la parte più difficile di una tesi: è banalmente impossibile ringraziare tutti e descrivere le mille emozioni di questi sei pazzi, incredibili anni.

Andiamo dunque con ordine: un primo, enorme ringraziamento al Prof. Scotti. Non solo per avermi ispirato professionalmente, ma anche per tutta la dedizione che ha dimostrato nei miei confronti. Anche nel mezzo di mattinate deliranti, mai le mie domande sono rimaste inascoltate. Le risate nel Suo studio mi hanno sempre migliorato le giornate, rendendo d'obbligo la tappa mattutina a disturbarLa. Se mai si chiedesse qual è l'impatto che ha avuto sulla mia vita tutto questo, conti che giro con le scarpe nere e i lacci gialli. Penso di non dover aggiungere altro.

Un grazie particolare ad Allegra e Riccardo, che sono stati prontissimi ad aiutarmi quando ero in procinto di lanciare il pc dalla finestra. Siete stati disponibili, gentilissimi e di grande aiuto: non dimenticherò mai i vostri consigli. Menzione d'onore ad Allegra, che probabilmente correggerà le bozze di qualche altra tesi anche all'altare: sei davvero una persona di cuore ad esserti impegnata anche per la mia tesi, chapeau.

Un grazie ai miei amici, ormai dottori di fama nazionale, che dico, mondiale: Fub, Grifa, Gera, Ste, Pucci, Marione, Davide e l'immenso Savoldi. La Dental non è stata la stessa quest'ultimo anno senza voi tutti!

Grazie anche ai miei compagni di classe, una squadra davvero fortissima. Ciascuno di voi mi ha aiutato più di quanto io abbia potuto fare con tutti voi messi insieme. Una particolare nota al mitico gruppo biblio del primo anno: siamo davvero alla fine, ma non mi sembra vero! Non dobbiamo ancora dare Anatomia?

Ovviamente un ringraziamento è d'obbligo nei confronti di tutti i Gialli. Il reparto di conservativa è stato per me una seconda casa, i Tutor dei veri amici. Non vi libererete di me tanto facilmente, ricordatevelo.

Grazie anche all'AISO e a tutte le persone incredibili che mi ha fatto conoscere.

Un ringraziamento speciale alla mia famiglia e alla famiglia di Alice che mi hanno sostenuto e supportato sin dal primo momento. Senza di voi non ce l'avrei mai fatta, siete stati la mia la mia ispirazione e un grande sostegno. Vi voglio bene!

Ringraziamento speciale a Edo, individuo molto più raccomandabile di me, per gli amici ormai noto come Andrea; aver condiviso questo folle percorso con te è stato un onore e un piacere. Sei un amico fantastico e ti assicuro che le ore di risate, schemi e autismi sono solo all'inizio. Specie l'autismo. Ti ho conosciuto che avevi ancora i capelli e non ti libererai di me finchè non li avrai persi tutti. Nota bene: non vale strapparseli.

Last but not least, il ringraziamento più dovuto di tutti. A colei che ha tollerato tutti i miei scleri in sessione esami e in pre-laurea, sopportandomi oltre che supportandomi. Alice, dopo otto anni insieme, le parole fra noi non servono più molto, ma vorrei poterti ringraziare un milione di volte per quello che sei stata, e sei tuttora, per me. Tutta la forza che mi hai dato ogni giorno, mi ha permesso di arrivare fino a questo momento. Siamo cresciuti insieme, facendo piccoli e grandi passi fianco a fianco: non posso davvero ringraziarti in quattro righe. I miei ringraziamenti te li farò di persona, per ora accontentati di questo: sei semplicemente meravigliosa come ragazza e come persona. GRAZIE.
In corner, grazie anche a Molly. Spero che un giorno imparerai a portarmi le ciabatte solo su esplicita richiesta. Dovresti smetterla di portarle in giro per casa come un trofeo. D'altronde è colpa mia che te l'ho insegnato.