Elemental analysis of contemporary dental materials regarding potential beryllium content

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Exposure to beryllium (Be) can lead to lung pathologies, such as chronic beryllium disease (CBD). This occupational illness has been more prevalent among dental technicians compared to the non-exposed population. Although most manufacturers state that dental materials are Be-free, this prevalence raises the question of whether the materials are completely devoid of Be-traces. Thus, the objective of the present study was to analyze the elemental composition, with emphasis on Be, of a wide range of commercially available dental materials frequently used by dental laboratories. Samples of 32 different materials were collected and analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES) and X-ray fluorescence spectroscopy. The results showed that the Be content was below the limit of quantification in all included samples (< 0.00005 mass-%). Therefore, it can be concluded that possible traces of Be were below clinical relevance in dental materials. Exposure of dental technicians to alternative Be sources should be further evaluated.

Abbreviations
CBD  Chronic Beryllium disease
BeLPT  Beryllium lymphocyte proliferation test
3Y-TZP  3 Yttria-stabilized tetragonal zirconia polycrystal
4Y-TZP  4 Yttria-stabilized tetragonal zirconia polycrystal
5Y-TZP  5 Yttria-stabilized tetragonal zirconia polycrystal
BeS  Be sensitization
ICP  Inductively coupled plasma
ICP-OES  Inductively coupled plasma-optical emission spectrometry
PEEK  Polyether ether ketone
PMMA  Polymethyl methacrylate
XRF  X-ray fluorescence spectroscopy

Beryllium (Be) is a chemical element and naturally occurring lightweight metal that finds industrial application in electronics, aerospace, and defense equipment¹². In the field of dentistry, Be has been used in nickel–chromium⁴,⁵ alloys with contents of up to 2.05 mass.%⁶ for the fabrication of prosthetic reconstructions. Be reduces the melting temperature, decreases the surface tension, and increases the bond strength between metals and ceramics⁷. Furthermore, it improves the castability and polishing of non-precious alloys.

Manufacturing and processing of Be-containing materials is highly toxic, and workers are exposed to the inhalation of Be particles, fumes, or solutions⁸. Brief exposure can lead to the development of a rare condition called acute berylliosis⁹, while long-term contact can cause Be sensitization (BeS)¹⁰ and chronic Be disease (CBD), also known as chronic berylliosis¹⁰,¹¹. An official statement of the American Thoracic Society assessed the prevalence of BeS between 0.9 and 14.6% and of CBD between 0.0 and 7.8%.¹² BeS represents an immunologically-mediated response to the metallic element without evidence of disease, while CBD is considered an incurable occupational...
lung condition and is often misdiagnosed with sarcoidosis or other granulomatous lung disorder. Symptoms of CBD are cough, dyspnea, fatigue, fever, night sweats, and weight reduction with potential progression to the loss of respiratory function. A history of occupational exposure to Be, positivity to the beryllium lymphocyte proliferation test (BeLPT) and a biopic examination, confirming a granulomatous inflammation of the lungs, are considered signs for definitive diagnosis of CBD. The incubation periods can last up to three decades. Due to the available evidence of carcinogenicity in humans and the risk of developing lung cancer by occupational exposure, Be and Be compounds have also been classified as category 1 carcinogens by the International Agency for Research on Cancer.

As a consequence of the increased occupational exposure to Be in dental laboratories, dental technicians appear at a higher risk of primarily developing CBD. Therefore, to protect workers, the Occupational Safety and Health Administration recently established a new limit of 0.2 µg of Be per cubic meter of air for an exposure duration of eight hours or of <2 µg of Be per cubic meter of air for more than 15 min. According to the current ISO standard for fixed and removable restorations (ISO 22674:2016), the limit value for Be in metallic materials is 0.02% (mass fraction). Exposure to Be is considered the causal agent for CBD development, and it remains unclear why dental technicians might be more affected. Therefore, the present study aimed to determine the elemental composition of commonly used dental materials and assess the exact amount of Be. Both, non-precious and precious metal alloys used to fabricate prosthetic reconstructions were included. Furthermore, different types of dental ceramics, titanium alloys, polymethyl methacrylate (PMMA), polyether ether ketone (PEEK), and polycarbonate were analyzed. Inductively coupled plasma-optical emission spectrometry (ICP-OES) represents a highly sensitive analytical technique with wide elemental coverage and was applied in the present study. The null hypothesis at study conceptualization assumed that evaluated materials contain traces of Be.

Material and methods

Study design. The analytical work was performed by the Institute of Applied Materials–Applied Material Physics of the Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany. The study proposal for cooperation between the Department of Prosthetic Dentistry and Clinic of Respiratory Medicine of the University of Freiburg, Freiburg, Germany, and the KIT has been approved and accepted by the Karlsruhe Nano Micro Facility in 2020.

Investigated materials and interdisciplinary cooperation. Four non-precious (Co–Cr) and five precious (Au) alloys were evaluated in the present investigation. In addition, seven ZrO2-based ceramics, two feldspathic ceramics, one lithium disilicate glass-ceramic (Li2Si2O5), one nano-fluorapatite glass-ceramic, and one nano-hybrid composite for veneering were included. Furthermore, five implant-supported abutments made of titanium or ZrO2, three PMMA-based materials, one polycarbonate, and one PEEK were examined. The evaluated samples represented a selection of the most frequently used materials for each category in two German dental laboratories, which provided the samples for elemental analysis. An overview of the investigated materials and their commercial name and article number is given in Table 1.

Preanalytical sample procession. The samples were divided into seven different groups depending on their different chemical composition. In Table 2 the preanalytical preparations and the chemical digestion are described for each group.

Inductively coupled plasma-optical emission spectrometry. Each sample solution was diluted several times depending on the concentration of the various elements. Instead of using volumetric dilution methods, the sample solution and ultrapure water were weighed (XP 205, Mettler-Toledo, Gießen, Germany). Analysis of the elements was accomplished with four different calibration solutions and an internal standard (Sc) by ICP-OES (iCAP 7600 ICP-OES Duo, Thermo Fisher Scientific Inc., Waltham, MA, USA) (Table 3). For Be the solution was, if necessary, matrix adapted (Ti, Co, Cu, Zr, Mo, Pd, In, W, Pt, Au). The range of the calibration solutions extended from 0.0005 to 0.01 mg/l. One to three wavelengths of Be were used for the calculation.

X-ray fluorescence spectroscopy. All samples were analyzed semiquantitative via X-ray fluorescence spectroscopy (XRF) (Pioneer S4, Bruker AXS, Karlsruhe, Germany) against different universal calibrations depending on the material of the samples (metal, oxide, etc.).

Quality control. The certified ICP calibration solutions (Aesar, Thermo Fisher (Kandel) GmbH, Karlsruhe, Germany, CPACChem, Bogomilovo, Bulgaria) were controlled with another certified ICP solution from a different producer (Agilent, Waldbronn, Germany; Merck, Darmstadt, Germany). The recovery of these standards in matrix-adapted solutions was between 95 and 105%.

Descriptive statistics. Results of the elemental analysis are described in Tables 2, 3, 4, 5 and 6 as the mean outcome, standard deviation (SD) and measurement uncertainty (±). Data regarding the oxides are semiquantitative results determined with XRF against a universal calibration. The results were normalized to 100.

Results

Detailed results of the ICP-OES elemental analysis are shown in Tables 4, 5, 6, 7 and 8.
Non-precious metal alloys. The limit of quantitation of Be in ICP-OES analysis is 0.1 mg/kg (Table 4). This Be level could not be measured in any non-precious dental alloy sample. Co was the main component in all the samples studied, followed by Cr. Heraenium PW (15.9 mass %) and Remanium Star (9.6 mass %) are the only ones containing W; Heraenium PW showed the highest amount of Fe (4.2 mass %).

Precious metal alloys. The main component of all precious alloys was Au (50.8–84.6 mass-%; Table 5). Maingold EH and Bio Maingold SG presented also Cu, Ag and Pt, whereas in Bio Herador GG the second main element besides Au was Pt. Heraloy G showed the highest amount of Pd (35.9 mass-%) and Ecobest the highest amount of Ag (29.1 mass-%). Be was not determined in any of the precious metal alloy samples tested (limit of quantitation of 0.04 mg/kg).

Oxide ceramics. Data of the three most present elements are semiquantitative and determined with XRF against a universal calibration. The concentration data can vary from more than 25 to < 5%. The results were normalized to 100. Be concentration of the tested oxide ceramics resulted below the measuring limit of 0.5 mg/kg (Table 6). All the oxide ceramics investigated had a Zr content between 66.1 and 68 mass%. Y was contained in all samples and DD cubeX² ML (7.6 mass-%) showed the highest content. Furthermore, Hf, which belongs to the group of heavy metals, was detected in all samples ranging between 1.29 and 1.55 mass %.

Other ceramics. As for the oxide ceramics, semiquantitative results were obtained with XRF against a universal calibration. The concentration data can vary by more than 100% at concentrations < 5% and the results were normalized to 100. None of the evaluated samples contained Be (limit of quantitation < 0.2 mg/kg) (Table 7). IPS e.max Press contained 76 mass-% SiO₂, while IPS e.max Ceram contained 49.1 mass-% SiO₂ with a higher content of ZrO₂ (9.49 mass-%) compared to the other groups. Gradia™ Plus is the only investigated

| Manufacturer            | Article no. | Sample name         | Material          |
|-------------------------|-------------|---------------------|-------------------|
| Kulzer                  | H-01028     | Heraenium EH        | Co–Cr alloy       |
| Kulzer                  | M-01068     | Heraenium PW        | Co–Cr alloy       |
| Dentaurum               | 102-620-00  | Remanium Star       | Co–Cr alloy       |
| Shera                   | 401,070     | Sheraheavy-Metal    | Co–Cr alloy       |
| Kulzer                  | SW12002-10  | Mainbond EH         | Au alloy          |
| Kulzer                  | SW12004-10  | Bio Herador GG      | Au alloy          |
| Kulzer                  | SW12035-0010| Bio Maingold SG     | Au alloy          |
| Kulzer                  | SW121616-10 | Heraloy G           | Au alloy          |
| Koon Edelmetalle        | 30,033      | Ecobest             | Au alloy          |
| Zirkonzahn              | ZRAB8001    | ICE Zircon Translucent | Oxide ceramic |
| Kuraray Noritake        | 6951        | Katana“ Zirconia ML | 3Y-TZP           |
| Zirkonzahn              | ZRFC8021A02 | Prettau® 4 Anterior® | 5Y-TZP           |
| Ivoclar Vivadent        | 725,196     | IPS e.max ZirCAD Prime | 3Y-TZP + 5Y-TZP |
| Pridenta                | 220,841     | prit®multidisc ZrO₂ Extra Translucent | 4Y-TZP |
| Dental Direkt           | G852017     | DD cubeX² ML        | 5Y-TZP           |
| Zirkonzahn              | ZRAB8001    | ICE Zircon Translucent A3 | Oxide ceramic |
| Ivoclar Vivadent        | 247,590     | IPS e.max Press LT  | Lithium disilicate glass-ceramic |
| Ivoclar Vivadent        | 168,424     | IPS e.max Ceram     | Nano-fluorapatite glass-ceramic |
| GC Europe               | 622,643     | Gradia™ Plus        | Nano-hybrid composite |
| Kuraray Noritake        | 35,101,010  | Ex-3                | Feldspathic ceramic |
| Kuraray Noritake        | 901,053     | Cerabien™ ZR        | Feldspathic ceramic |
| Zirkonzahn              | ZRAD8001    | Prettau® Zirkon 95H10 | Oxide ceramic |
| Straumann               | 48,710      | RN Varinbase        | Implant abutment  |
| SIC                     | 935,727     | SIC Standard Abutment | Implant abutment  |
| Kulzer                  | 30,503,871  | cara i-abutment® titanium | Implant abutment  |
| Zirkonzahn              | BSAF0893    | Set ZZ Base B-C-ABCH | Implant abutment  |
| Tizian Blank            | 624,939     | Tizian Blank Zirkonumdioxid | Implant abutment  |
| Organical CAD/CAM       | BL00067-3700| Organic PMMA ECO    | PMMA             |
| Organical CAD/CAM       | N/A         | Organic PMMA DISC Multicolour 5-Layer | PMMA |
| Organical CAD/CAM       | N/A         | Organic PMMA ECO Clear | PMMA |
| Ernst Hinrichs Dental   | 242,774     | JUVORA® PEEK        | PEEK             |
| Schütz Dental           | 220,361     | Tizian Blank        | Polycarbonate    |

Table 1. Investigated materials.
nano-hybrid composite containing BaO (41.3 mass-%), the second-largest component in this material after SiO₂ (49.8 mass-%).

**Implant abutments.** The elemental analysis of the implant abutments showed that the SIC standard abutment and the cara i-abutment® titanium had a similar elemental composition (Table 8). Both consisted of approximately 90 mass-% Ti, 4 mass-% V and 6 mass-% Al. The RN Variobase abutment was measured to be 100 mass-% Ti (with a standard deviation of 0.5 mass-% and measurement uncertainty of 2.4 mass-%). The values for Al, Ti and V were below the respective detection limit. Therefore, a possible Be content was below the detection limit for all the evaluated samples.
Table 3. Instrument settings for ICP-OES.

| Element | Setting                          |
|---------|----------------------------------|
| ICP     | Peristaltic pump                 |
|         | Mira Mist peek nebulizer         |
|         | Cyclon teflon spray chamber      |
|         | Ceramic torch with ceramic injector tube |
| RF power (W) | 1150                         |
| Auxiliary gas flow | 0.5 (L/min) for main compounds |
|         | 1.0 (L/min) for high matrix content |

Wavelength (nm)

| Element | Wavelength (nm) |
|---------|-----------------|
| Be      | 234.861; 313.042; 313.107 |
| Al      | 176.638; 308.215; 394.401; 396.152 |
| Si      | 212.412; 221.667; 251.611 |
| K       | 766.490; 769.896 |
| Ti      | 323.452; 334.188; 334.941; 337.280; 338.376 |
| V       | 268.796; 292.464; 309.464 |
| Cr      | 205.560; 206.157; 267.716 |
| Co      | 228.616; 230.786; 238.892 |
| Cu      | 213.598; 324.754; 327.396 |
| Zn      | 202.548; 206.200; 213.856 |
| Ga      | 287.424; 294.364; 403.298; 417.206 |
| Y       | 371.030; 377.433; 437.494 |
| Zr      | 339.198; 346.823; 348.115; 349.621; 357.685; 383.676 |
| Mo      | 202.030; 203.844; 204.598 |
| Pd      | 324.270; 340.458; 360.955 |
| Ag      | 243.779; 32.068; 338.289 |
| In      | 230.606; 303.936; 325.609; 410.172 |
| Sn      | 175.790; 189.989; 181.120 |
| Ba      | 230.424; 233.527; 413.066 |
| Hf      | 251.303; 264.141; 277.336 |
| W       | 207.911; 220.448; 224.875 |
| Pt      | 177.709; 203.646; 214.423; 224.552 |
| Au      | 197.819; 208.209; 211.068; 242.795; 267.595 |

Table 4. ICP-OES results of non-precious metal alloys. LOQ limit of quantitation, SD standard deviation, ±: measurement uncertainty.
The analysis of the three PMMA, one PEEK, and one polycarbonate material revealed a Be content < 0.08 mg/kg for all the evaluated samples (Table 9).

**Discussion**

The objective of this study was to investigate multiple currently used dental materials concerning their possible Be content. To our best knowledge, no studies have conducted an elemental analysis for the detection of Be using a comparable broad spectrum of different dental materials, which includes precious and non-precious alloys, ceramics, PMMA, PEEK, and polycarbonate. Importantly, due to the low occupational exposure limits (0.2 mg Be/m³ air), a very sensitive methodology is necessary to determine the concentration of Be at ultra-trace levels.

Be has been widely used in the past decades to manufacture dental appliances. To date, Be-exposure is considered "a modern industrial hazard" which can lead to sensitization and CBD, chronic lung disease. A key factor for the management of CBD is the prevention of workplace-related and environmental Be exposure. Frye et al. described a cluster of workers in an industry not directly related to Be processing and suffering from BeS caused by the high levels of Be contained in the concrete dust. Appropriate protective equipment and preventive measures are mandatory to reduce the risk of respiratory diseases. In addition, routine medical examinations should be provided as for other high-exposure worker categories. Although exposure to Be in working places is being strictly regulated by the Occupation Health and Safety Administration, controlling is difficult.

Dental technicians are at higher risk of developing occupational respiratory disorders such as pneumoconiosis, caused by exposure to dust while handling dental materials. They still seem to represent a population at higher risk of Be-associated disorders compared to non-exposed workers despite the increasingly use of Be-free materials. Furthermore, while the term "beryllium free" is used by several manufacturers to name their dental products, the concentration threshold for defining a material "free" from Be is still not defined. Further research groups aimed to assess the amount of Be contained in dental materials. Alkmin et al. investigated the microstructural

### Table 5. ICP-OES results of precious metal alloys. LOQ limit of quantitation, SD standard deviation, ±: measurement uncertainty; n.a. not available.

| Element | Unit | LOQ    | Mainbond EH | Bio Herador GG | Bio Maingold SG | Heraloy G | Ecobest |
|---------|------|--------|-------------|---------------|-----------------|-----------|---------|
| Be      | mass-% | 0.000004 | < 0.000004 | < 0.000004 | < 0.000004 | < 0.000004 | < 0.000004 |
| Fe      | mass-% | 0.200  | < 0.200     | 0.983        | 0.246          | < 0.200   | 0.318   | 0.080   | 0.230   | 0.058  |
| Cu      | mass-% | 0.53   | 7.43        | 0.03         | 0.37           | < 0.53    | 12.1    | 0.1     | 0.6     | < 0.53  |
| Zn      | mass-% | 0.100  | 0.482       | 0.003        | 0.024          | < 0.100   | 0.473   | 0.006   | 0.024   | < 0.100 |
| Ga      | mass-% | 0.13   | n.a         | < 0.13       | n.a            | –        | –       | 1.97    | 0.02    | 0.10   |
| Pd      | mass-% | 0.40   | < 0.40      | < 0.40       | < 0.40         | < 0.40    | 35.9    | 0.1     | 3.6     | 9.73   | 0.10   | 0.49   |
| Ag      | mass-% | 0.30   | 1.52        | n.a          | –              | 14.3      | 1.43    | n.a     | 29.1    | 0.11   |
| In      | mass-% | 0.30   | < 0.30      | –            | 1.65           | 0.01     | 0.08    | < 0.30  | –       | 8.21   | 0.11   | 0.41   | 3.96   | 0.01   | 0.20   |
| Pt      | mass-% | 0.12   | 8.36        | 0.04         | 3.59           | 11.2      | 0.1     | 3.59    | 3.85    | 0.01   | 3.59   | < 0.12 |
| Au      | mass-% | 0.2    | 69.0        | 0.5          | 4.2            | 84.6      | 0.8     | 5.2     | 70.2    | 0.5    | 4.3    | 50.8   | 0.5    | 3.1    | 56.3   | 0.3    | 3.4    |
| Total   | mass-% | 100.472| 98.433      | 100.923      | 97.198         | 97.198    | 100.680 |

### Table 6. ICP-OES results of oxide ceramics. LOQ limit of quantitation, SD standard deviation, ±: measurement uncertainty.

| Element | Unit | LOQ    | ICE Zircon Translucent | Katana Zirconia ML | Prethau 4 Anterior Dispersive | IPS e.max ZirCAD Prime | priti multidisc ZrO2 Extra Translucent | DD cubeX2 ML | ICE Zircon Translucent A3 |
|---------|------|--------|-------------------------|--------------------|-----------------------------|------------------------|----------------------------------------|--------------|-------------------------|
| Be      | mass-% | 0.00005 | < 0.00005              | < 0.00005          | < 0.00005                   | < 0.00005              | < 0.00005                              | < 0.00005   | < 0.00005               |
| Y       | mass-% | 0.01   | 4.29                    | 0.03               | 0.21                        | 5.88                   | 0.13                                   | 0.28         | 6.49                    | 0.03               | 0.32   | 3.88   | 0.05   | 0.27   | 5.24   | 0.02   | 0.26   | 7.56    | 0.13   | 0.38   | 4.25   | 0.08   | 0.21   |
| Zr      | mass-% | 2.6    | 68.0                    | 0.6                | 3.4                         | 67.3                   | 1.5                                   | 3.4          | 66.1                   | 0.3                | 3.3   | 67.5   | 0.8    | 3.4   | 67.3   | 0.3    | 3.4   | 67.9   | 1.3    | 3.4   |
| Hf      | mass-% | 0.02   | 1.49                    | 0.01               | 0.07                        | 1.29                   | 0.03                                  | 0.06         | 1.29                   | 0.01               | 0.06  | 1.50   | 0.02   | 0.08  | 1.45   | 0.03   | 0.07  | 1.42   | 0.03   | 0.07  | 1.55   | 0.03   | 0.08  |
| Total   | mass-% | 73.78  | 74.17                   | 73.88              | 74.38                       | 73.99                  | 74.28                                  | 73.70        | 74.28                  | 73.70              | 74.28 | 73.70 |

**PMMA, PEEK, polycarbonate.** The analysis of the three PMMA, one PEEK, and one polycarbonate material revealed a Be content < 0.08 mg/kg for all the evaluated samples (Table 9).
Table 7. ICP-OES results of further investigated ceramic materials. LOQ limit of quantitation, SD standard deviation, ±: measurement uncertainty.

| Element | Unit | LOQ | IPS e.max Press LT | IPS e.max Ceram | GradiaTM Plus | Ex-3 | Cerabien™ ZR | Prettau® Zirkon 95H10 |
|---------|------|-----|--------------------|----------------|--------------|------|---------------|-------------------------|
| Be      | mass-% | 0.00002 | < 0.00002 | < 0.00002 | < 0.00002 | < 0.00002 | < 0.00002 | < 0.00002 |
| Na2O    | mass-% | 0.42 | 3.69 | 0.21 | 4.71 | 4.15 | - | - |
| MgO     | mass-% | 0.26 | - | 0.32 | 0.30 | - | - | - |
| Al2O3   | mass-% | 2.22 | 8.08 | 6.89 | 15.9 | 12.6 | 0.6 | - |
| SiO2    | mass-% | 76.0 | 49.1 | 49.8 | 64.9 | 71.70 | 5.41 | - |
| P2O5    | mass-% | 1.98 | 0.12 | 0.03 | - | - | - | - |
| SO3     | mass-% | 0.06 | 0.05 | 0.74 | 0.04 | 0.03 | - | - |
| K2O     | mass-% | 7.53 | 7.67 | 0.16 | 11.0 | 7.81 | 0.24 | - |
| CaO     | mass-% | 0.06 | 1.99 | 0.13 | 0.80 | 0.75 | 0.06 | - |
| TiO2    | mass-% | - | - | 1.41 | 0.30 | - | - | - |
| Cr2O3   | mass-% | 0.12 | 0.04 | - | 0.07 | 0.08 | - | - |
| MnO     | mass-% | - | - | - | - | - | - | - |
| Fe2O3   | mass-% | 0.26 | 0.09 | 0.09 | 0.15 | 0.15 | 0.26 | - |
| Co2O3   | mass-% | - | - | - | - | - | - | - |
| NiO     | mass-% | - | - | - | - | - | - | - |
| CuO     | mass-% | - | - | - | - | - | - | - |
| ZnO     | mass-% | 4.67 | 5.01 | - | - | 0.22 | - | 0.06 |
| SrO     | mass-% | 2.70 | 8.37 | 0.35 | - | - | - | - |
| Y2O3    | mass-% | - | - | 0.53 | 0.10 | 0.15 | - | 5.03 |
| ZrO2    | mass-% | 1.40 | 9.49 | 0.64 | 0.56 | 85.80 | - | - |
| Nb2O5   | mass-% | - | - | - | - | - | 0.71 | - |
| SmO     | mass-% | - | - | 3.78 | - | - | - | - |
| Sb2O3   | mass-% | - | - | - | - | 1.15 | - | 1.24 |
| BaO     | mass-% | - | - | - | 41.3 | - | - | - |
| La2O3   | mass-% | 0.50 | - | - | - | - | - | - |
| Ce2O3   | mass-% | 1.00 | 0.58 | - | - | 0.42 | - | - |
| Tb2O3   | mass-% | 0.82 | - | - | - | - | - | - |
| HfO2    | mass-% | - | - | - | - | - | 1.80 | - |
| Total   | mass-% | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | - |
characteristics of eight Ni–Cr alloys in the commerce. The samples were analyzed using an inductively coupled plasma spectrometer (ICP-OES). Of the eight investigated alloys, five presented Be traces up to 2.05 mass-% and in two of these cases, the Be amount was not reported by the manufacturer.

There are different methods for ICP elemental analysis. On one side, inductively coupled plasma mass spectrometry relies on a high-temperature ionization source paired with a mass spectrometer. After nebulization, the samples are atomized, and ions are generated for the mass analysis. On the other side, ICP-OES technology is based on the light transmission at specific wavelengths by atoms that move to a lower energy level. Element type and concentration are calculated based on the position and the intensity of the photon rays. All the analytical investigations of this study were performed with ICP-OES, which allows for precise multi-element tracing with high sensitivity and low detection limits.

Within the limit of quantification of the adapted methodic, Be traces ranged from below 0.000004 to 0.00005 mass-% depending on the group of materials analyzed. Based on these analyses, conducted at the ultra-trace level, it can be assessed that traces of Be are not of clinical significance in the evaluated samples. Therefore, the null hypothesis of the present investigation, assuming traces of Be are contained in the investigated dental materials, has to be rejected. Be was not found in the investigated materials, but further independent studies should address the elemental composition of used dental materials, focusing on heavy metals. A thorough understanding of health risks and the development of strategies to minimize occupational exposure to hazards should be continually pursued.

These results, however, raise further questions regarding the increased prevalence of Be-associated disorders in dental technicians and an evidence-based explanation. Firstly, some of the studies were conducted several years ago, and the identification of health hazards, as well as the consequent restrictions adopted, might have caused the modification of the material compositions by the manufacturers. Secondly, despite the large-scale screening, the analyzed samples represent only a minimal fraction of the materials currently used in dental laboratories. Finally, it should also be considered that this study included only materials used in German dental laboratories, while most recent articles describing the prevalence of Be-associated diseases in dental technicians were assessed in other countries. Despite the analyses of a large amount of samples by several sensitive methods, this study has a few limitations, including the restriction of the geographic area to Germany and to certain types of material. Analogue evaluations should be considered in future investigations involving a broader group of materials and different countries.

Conclusions
Based on the described elemental analysis, the following conclusions can be drawn:

- The applied ICP-OES method allowed for a highly sensitive elemental analysis at ultra-trace levels.
- Be concentration was below the respective limit of quantification (< 0.00005 mass-%) for all the evaluated samples.
- Further studies are needed to assess the Be amount in currently commercialized dental materials.

Data availability
All data generated or analysed during this study are included in this published article.
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Author contributions

B.C.S., F.B. and S.P. conceived the ideas; F.B. and S.P. collected the data; T.B. analyzed the data; F.B. and S.P. led the writing; B.C.S., C.W., G.W., T.B. and D.S. revised and approved the manuscript; C.W. and G.W. provided the resources; B.C.S. and D.S. supervised the research.

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Competing interests

The authors declare no competing interests.
