Enhancing Distraction Osteogenesis With Carbon Fiber Reinforced Polyether Ether Ketone Bone Pins and a Three-Dimensional Printed Transfer Device to Permit Artifact-Free Three-Dimensional Magnetic Resonance Imaging

Karen A. Eley, FRCR, DPhil,[*] Mehran Moazen, PhD,[†] Gaspar Delso, PhD,[*] Maryam Javidan, MSc,[†] Joshua Kaggie, PhD,[*] Deepak M. Kalaskar, PhD,[‡] Jonathan C. Knowles, PhD, CSci,[§||¶#] Nazanin Owji, BSc, MSc,[§] and Stephen R. Watt-Smith, FDSRCS, MD[**]

Objectives: To: (1) design an artifact-free 3D-printed MR-safe temporary transfer device, (2) engineer bone-pins from carbon fiber reinforced polyether ether ketone (CFR-PEEK), (3) evaluate the imaging artifacts of CFR-PEEK, and (4) confirm the osteointegration potential of CFR-PEEK, thus enhancing 3D-planning of bony advancements in hemifacial microsomia using sequential magnetic resonance imaging (MRI).

Study Design: Engineered CRF-PEEK bone pins and a 3D printed ex-fix device were implanted into a sheep head and imaged with MRI and computed tomography . The osseointegration and bony compatibility potential of CFR-PEEK was assessed with scanning electron microscopy images of MC3T3 preosteoblast cells on the surface of the material.

Results: The CFR-PEEK pins resulted in a signal void equivalent to the dimension of the pin, with no adjacent areas of MR-signal loss or computed tomography artifact. MCT3 cells adhered and proliferated on the surface of the discs by forming a monolayer of cells, confirming compatibility and osseointegration potential.

Conclusion: A 3D printed transfer device could be utilized temporarily during MRI to permit artifact-free 3D planning. CFR-PEEK pins eliminate imaging artifact permitting sequential MRI examination. In combination, this has the potential to enhance distraction osteogenesis, by permitting accurate three-dimensional planning without ionizing radiation.

Key Words: Distraction osteogenesis, hemifacial microsomia, magnetic resonance imaging, mandible, osseointegration, three-dimensional printing

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From the *Department of Radiology, University of Cambridge, Cambridge Biomedical Campus, Cambridge; †Department of Mechanical Engineering, University College London; ‡Division of Surgery and Interventional Sciences, UCL Institute of Orthopedics and Musculoskeletal Sciences, Stanmore; §Biomaterials and Tissue Engineering, UCL Eastman Dental Institute; ||The Discoveries Centre for Regenerative and Precision Medicine, UCL Campus, London, UK; ¶Department of Nanobiomedical Science and BK21 PLUS NBM Global Research Center for Regenerative Medicine, Dankook University; #UCL Eastman-Korea Dental Medicine Innovation Centre, Dankook University, Cheonan, Republic of Korea; and **UCL Eastman Dental Institute, London, UK.

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Address correspondence and reprint requests to Karen A. Eley, FRCR, DPhil, Department of Radiology University of Cambridge School of Clinical Medicine Box 218, Cambridge Biomedical Campus, Cambridge CB2 0QQ, UK; E-mail: Karen.a.eley@gmail.com

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Craniofacial microsomia is a developmental anomaly of the first and/or second pharyngeal arch, and is considered to be the second most common congenital facial condition following cleft lip and palate.[1] Mandibular involvement is a continuum from hemi-hypoplasia through to abnormal configuration, with absence of the condyle and ramus. Unilateral asymmetry poses particular surgical challenges. Distraction osteogenesis is typically employed to lengthen the mandible and provide gradual increase in size of the soft tissue envelope. Planning the three-dimensional (3D) mandibular advancement is often reliant upon two-dimensional projections of anatomy through the use of radiographs in an attempt to minimize radiation exposure in young patients. The stainless-steel or titanium distraction device and pins result in significant metallic streak artifact limiting the use of 3D imaging with cone-beam or conventional computed tomography (CT) for sequential mapping of bony advancement, and stainless-steel devices are largely contraindicated in magnetic resonance imaging (MRI). Even if streak artifacts were eliminated on CT, the potential adverse effects of ionizing radiation in these young patients raise serious ethical concerns in terms of repeated exposure to monitor and predict subsequent distraction advancements. A nonferrous, artifact-free distraction device would permit sequential nonionizing imaging with MRI, thus opening up the possibility of accurate 3D planning of bone and soft tissue advancements. The incorporation of MRI "Black Bone" and ultra-short echo time techniques (such as gradient echo (GRE) techniques including 3D volumetric interpolated breath-hold, as well as zero-echo time (ZTE) and pointwise encoding time reduction with radial acquisition (PETRA) sequences) provide not only the potential for 3D reconstructed imaging of the bone of the craniofacial skeleton but also the option for multi-planar reconstruction of the acquired volume.[2–8]

Polyether ether ketone (PEEK) is increasingly being utilized as an alternative to more traditional screws and implants made from titanium or stainless steel.[9] Reported clinical outcomes are comparable to traditional devices, with the added benefit of minimizing imaging artifacts. The addition of carbon fiber to form reinforced-PEEK (ie, CFR-PEEK) improves the mechanical properties of the PEEK. With potential for osseointegration, CFR-PEEK distraction pins may offer similar capabilities to currently utilized titanium or stainless-steel distraction pins,[10] but have not been explored for cranio-maxillofacial applications.

We hypothesized that CFR-PEEK pins would permit artifact-free (and ionizing radiation-free) MRI examination, thus enhancing 3D planning of sequential bone advancements. Whilst recognizing that some surgeons prefer intra-oral devices for mandibular distraction, the ease with which external fixator distractor devices can be removed from the distraction pins lends itself to the option for replacement with a temporary holding device for use during imaging acquisition, and provides a good starting point for initial investigation.

The objectives of this study were therefore 4-fold:

1. to design a distraction device that could be used as a temporary device during MRI examination which was artifact free,
2. to engineer bone pins from CFR-PEEK,
3. evaluate the imaging effects of CFR-PEEK in comparison with titanium on multi-planar and 3D reconstructed imaging, and
4. confirm the osteointegration potential of CFR-PEEK.

MATERIALS AND METHODS

Design

Utilizing standard mandibular distractor pins as the starting point, we engineered distractor bone pins from CFR-PEEK with a diameter of 3 mm. Comparable pins of 3 mm were engineered from titanium. A temporary external-fixator (ex-fix) transfer device was designed (SolidWorks, Dassault Systems, France) so as to permit easy transfer onto the distraction pins whilst permitting access for removal of the metal distraction device. The temporary device was 3D printed in translucent acrylic-based resin using stereolithography (SLA - Formlabs, MA), and thus MR-safe.

Radiological Imaging

To ascertain the associated imaging artifacts of the device and pins, 4 CFR-PEEK pins were implanted into the mandible of a dead animal model (sheep head) and the transfer device attached. MRI was acquired on both 1.5T and 3T magnets (GE MR450w and GE PETMR, GE Medical Systems Ltd, Buckinghamshire, UK) and 1.5T magnet (Siemens Prisma Fit, Siemens Healthcare Limited, Erlangen, Germany). The imaging protocol included a “Black Bone” GRE sequence[2,3] and ZTE on both 1.5 and 3T GE systems, and PETRA and volumetric interpolated breath-hold on a 1.5T Siemens system. In addition, T2 FLAIR and FSPGR imaging was acquired on a 3T magnet following the insertion of a 10 mm CFR-PEEK rod into the mouth of the sheep alongside the distraction device. Comparable CT imaging was acquired with bone and soft tissue algorithms.

The imaging protocol was repeated on a second animal model with 4 titanium pins and the temporary distractor device, and on a third animal model with 1 CFR-PEEK and 1 titanium distraction pin on the same side of the mandible. A fourth animal was imaged without intervention to provide a control. Conventional stainless-steel distraction devices and pins could not be evaluated in view of their non-MRI compatibility due to instability in the animal model.

MRI and CT artifacts were assessed on multiplanar imaging. Using 3D multi-planar reformats, the mandible was visualized at the point where the pins were crossing parallel to the bone, and the image magnified. The maximum diameter of the signal void for each of the 4 pins was measured using Osirix (Osirix MD, Version 10.0.5, Pixmeo SARL, Switzerland) and a mean result obtained. Three-dimensional reconstructed images of the skull and facial skeleton were produced using manual segmentation on Fovia (*High Definition Volume Rendering*, Fovia Inc, Palo Alto, CA) using previously described segmentation techniques.[1,2]

Cell Seeding

CFR-PEEK discs with an outer diameter of 10 mm and thickness of 0.5 mm were prepared. The specimens were sterilized using a standard autoclaving protocol. Samples were surface treated using oxygen plasma for 5 minutes to increase hydrophilicity of samples and thus encourage cellular interactions.[11] MC3T3 cell line (osteoblast precursor cell line derived from mouse calvaria) was cultured in polystyrene flasks in Dulbecco’s modified Eagle’s medium (Gibco, Life Technologies Ltd, Paisley, UK) supplemented with 10% fetal bovine serum (FBS), 50 IU/ml of penicillin and 50 μg/ml of streptomycin at 37°C. Confluent cells were then passaged by using trypsin-EDTA (Invitrogen, Paisley, UK) over the CFR-PEEK discs.

Scanning Electron Microscopy (SEM) Images

Specimens were fixed in 3% glutaraldehyde and 0.1 M cacodylate buffer and stored at 4°C overnight. Serial ethyl alcohol dehydration was carried out the next day for 10 min at each concentration and the discs were subsequently dried in hexamethyldisilazane and left in the hood for 1 hour. Specimens were then coated with 95% gold and 5% palladium (Polaron E5000 Sputter Coater, Quoram Technologies, Laughton, UK) and SEM (Philips XL30 Field Emission SEM, Amsterdam, Netherlands) was used to visualize the surface of the specimen discs.

RESULTS

The temporary ex-fix transfer device with CFR-PEEK pins in-situ in the sheep head, the CFR-PEEK and titanium pins are shown in Figure 1. As demonstrated in Figure 2A to D, the CFR-PEEK pins, 10 mm rod and transfer device could be visualized on CT, but did not result in any streak-artifact.

The transfer device was not visualized on any of the MRI sequences and the CFR-PEEK pins and rod were visualized as an area of signal void (Fig. 3). The necessary drilling into the mandible to insert the distractor pins resulted in the introduction of a small volume of air, which is also seen as an area of signal void on all MRI sequences; this artifact was reduced on ZTE/PETRA sequences. The increased signal void due to the presence of air is further shown in Figure 4, where the 10 mm CFR-PEEK rod is shown in contact with air within the oral cavity. Measurement of the CFR-PEEK rod on FLAIR and FSPGR sequences and CT imaging at sites distant from air were comparable, and correlated with the known 10 mm diameter.

The titanium pins resulted in increased artifact on all MRI sequences, with an increased mean measurement for the intraosseous signal void resulting from the distraction pins equating to, on average, double the diameter of the pin (Supplementary Digital Content, Table 1, http://links.lww.com/SCS/B710 Fig. 3). CT maximum interpolation images (Fig. 2E–G) demonstrate the pins and transfer device across the 3 sheep heads to highlight the volume

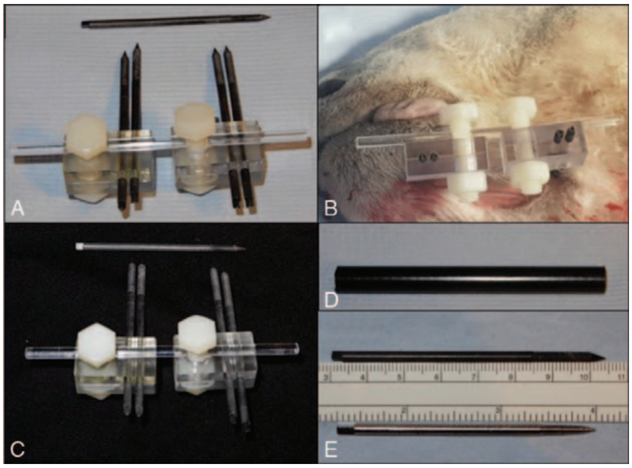

FIGURE 1. (A) CRF-PEEK distraction pin and 4 pins held within the temporary ex-fix transfer device which was 3D printed in PolyJet resin; (B) the CRF-PEEK pins and temporary ex-fix transfer device in situ within the mandible of a sheep; (C) corresponding titanium pin and 4 pins held within the transfer device; (D) 10 mm CRF-PEEK rod; and (E) CRF-PEEK distraction pin (top) and comparable titanium pin (bottom). CRF-PEEK, carbon fiber reinforced polyether ether ketone.

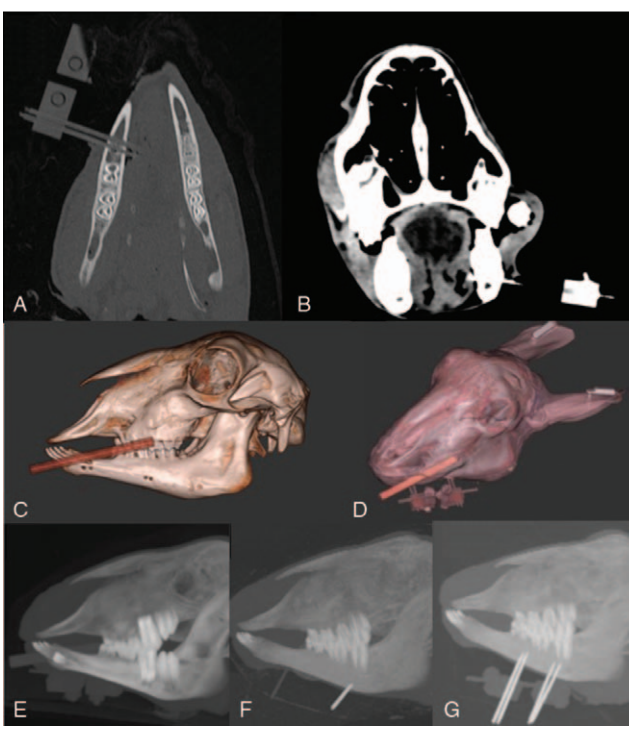

FIGURE 2. (A) Oblique axial bone algorithm CT imaging showing the absence of artifact from the CRF-PEEK pin and temporary transfer device, (B) oblique coronal soft tissue algorithm CT again demonstrating the CRF-PEEK pin and transfer device, with a 10 mm CRF-PEEK rod within the left maxillary buccal sulcus, (C) 3D volume rendered CT bone image showing the nonvisualization of the CRF-PEEK pins and transfer device compared to the 10 mm CRF-PEEK rod, (D) 3D volume rendered CT soft tissues to demonstrate the CRF-PEEK pins, rod, and transfer device in situ. CT maximum intensity projection (MIP) imaging of the sheep head with (E) 4 CRF-PEEK distraction pins with transfer device, plus 10 mm CRF-PEEK rod, (F) 1 CRF-PEEK (anterior) and 1 titanium (posterior) distraction pin, (G) four titanium distractor pins and CT, computed tomography; CRF-PEEK, carbon fiber reinforced polyether ether ketone.

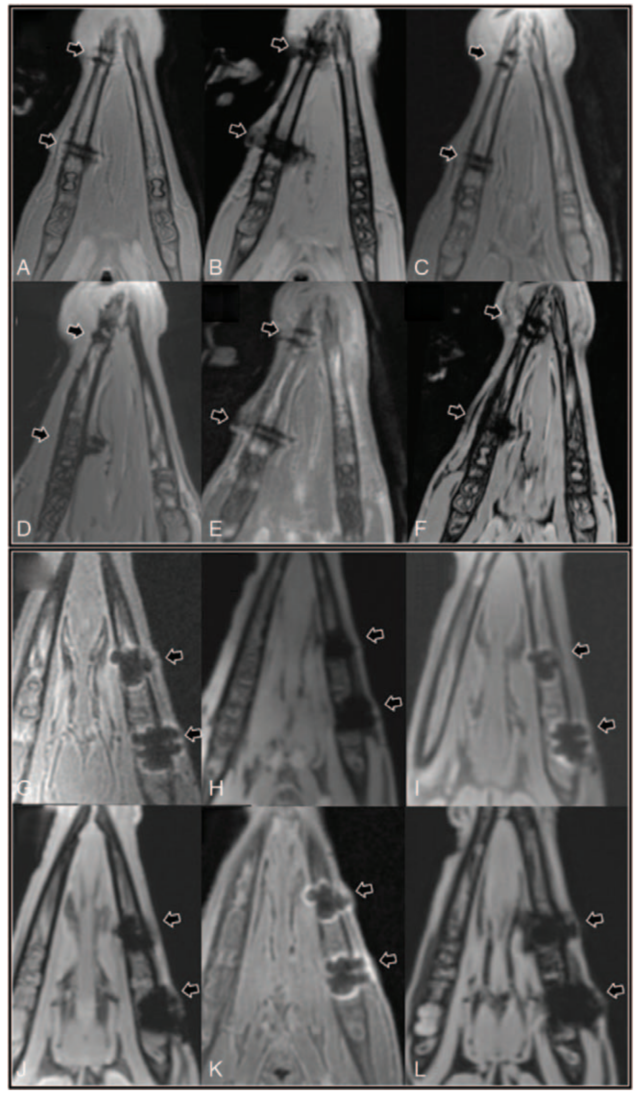

FIGURE 3. Oblique axial magnetic resonance imaging images of the carbon fiber reinforced polyether ether ketone distraction pin from (A) 1.5T ZTE, (B) 1.5T GRE BB, (C) 3T ZTE, (D) 3T GRE BB, (E) 1.5T PETRA and (F) 1.5T VIBE. Oblique axial imaging of the mandible demonstrating the artifact associated with the 4 titanium pins on (G) 1.5T ZTE, (H) 1.5T GRE BB, (I) 3T ZTE, (J) 3T GRE BB, (K) 1.5T PETRA and (L) 1.5T VIBE. GRE, gradient echo; PETRA, pointwise encoding time reduction with radial acquisition; VIBE, volumetric interpolated breath-hold; ZTE, zero-echo time.

of metalwork in the 2nd head. In this case, where there were 4 titanium pins this resulted in notable streak artifact on CT (Fig. 5).

The "Black Bone" sequences in view of their volume acquisitions permitted multi-planar reformats of the bone at any angle, thus providing optimal visualization of the mandible and distraction devices, comparable to CT. In addition, the MRI data was used to successfully produce 3D reconstructed images of the mandible (Fig. 6) to further highlight the benefit of the artifact-free devices.

The nontoxicity of the CFR-PEEK and its osseointegration potential were confirmed with SEM images (Fig. 7). The morphology and proliferation of MC3T3 cells on the surface of the discs were successfully observed. This showed formation of a monolayer of cells with apparent cell morphology, where the process of cell division could also be detected. The overall cell alignment exhibited an elongated and uniform network covering the surface of the material.

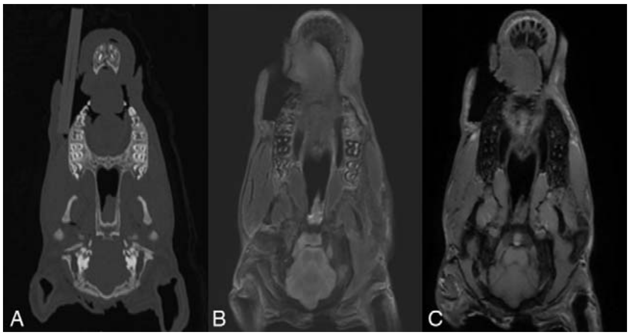

FIGURE 4. 10 mm CRF-PEEK rod within the left maxillary buccal sulcus on (A) computed tomography bone algorithm, (B) 3T FLAIR and (C) 3T FSPGR imaging, demonstrating the absence of artifact, and inability to distinguish air from the CRF-PEEK on FSPGR imaging. CRF-PEEK, carbon fiber reinforced polyether ether ketone.

DISCUSSION

Titanium metal alloys are frequently used in surgery because of their relatively low magnetic susceptibility artifact when compared with stainless steel.[9–10,12–14] Titanium offers a similar material strength to stainless steel at reduced weight, which combined with its biocompatibility and osseointegration makes it ideally suited to implanted medical devices. However, its significantly increased elastic modulus compared to bone may result in bone resorption and implant fracture.[15] PEEK was originally developed by the aerospace industry with potential for high-load, high-temperature applications. By the late 1990s PEEK was increasingly utilized as an alternative to conventional metallic implants in view of its biocompatibility and improved compatibility with diagnostic imaging. In addition, it has been shown to cause fewer hypersensitive and allergic reactions than titanium.[15] Carbon-fiber-reinforced polyether ether ketone (CFR-PEEK) has a modulus very similar to bone and an ability to withstand prolonged fatigue strain, and may be able to avoid potential issues such as stress shielding and bone resorption.[10] To our knowledge, unlike PEEK, CFR-PEEK has not previously been described in the literature for cranio-maxillofacial applications.

We have demonstrated the potential benefit of a temporary distraction device and CFR-PEEK distraction pins which result in minimal signal void on MRI sequences, and absence of streak artifact on CT. The MRI sequences explored are amenable to multiplanar and 3D reconstruction and therefore provide a feasible alternative to CT imaging. 3D reconstructed images of the mandible were created using manual segmentation techniques for this study. We have previously reported our automated segmentation algorithms, which were not transferrable to the sheep heads, but would be applicable in clinical practice providing excellent potential for 3D visualization of bony advancements.[16,17]

FIGURE 5. Computed tomography imaging of the sheep head with four titanium distractor pins and temporary transfer device in-situ. This demonstrates metallic streak artifact (arrows) seen on both bone algorithm (A&B) and soft tissue algorithms (C&D).

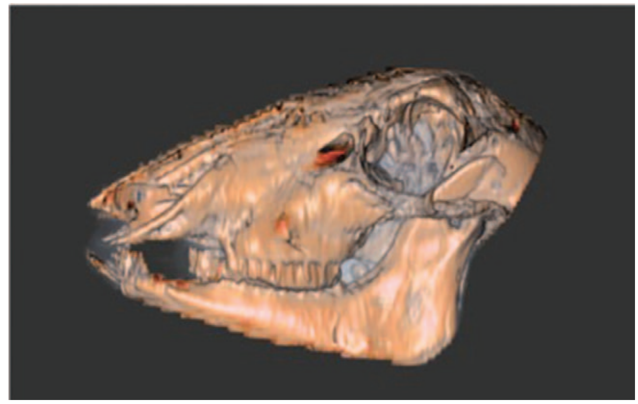

FIGURE 6. 3D volume rendered BB image of the craniofacial skeleton of the first head with nonvisualization of the carbon fiber reinforced polyether ether ketone pins, rod, and temporary transfer device.

GRE sequences resulted in increased artifact from adjacent air compared to the ZTE sequences. However, this is unlikely to be problematic in routine imaging since the postoperative air would be either resorbed or replaced with tissue fluids, for example, blood. No artifact was seen on CT imaging with the CFR-PEEK pins. In comparison, despite their small diameter the titanium pins resulted in noticeable streak artifact on CT, and were associated with an increased area of signal void on all MRI sequences.

Investigating cellular morphology is a practical approach in evaluation of osteogenic potential of biomaterials. Cell interaction with the material surface, in the complex process of cell attachment, can also determine osseointegration. In this study cell proliferation demonstrated on electron microscopy proposes the potential for osseointegration of the CFR-PEEK discs. This can be beneficial in distraction pins to maintain stability, permit accurate bony advancements and prevent migration of the pins. However, in order to confirm the findings, assessment of cell metabolic activity and DNA content can provide a more accurate indication of how the cells respond to the material surface.

With the potential for osseointegration, CFR-PEEK pins provide a viable alternative to titanium or stainless steel bone pins, which when used in combination with a 3D printed temporary transfer device, yields artifact-free imaging to enhance 3D planning of sequential bone advancements. The use of the temporary 3D printed distraction device is of course only possible when utilizing a traditional external fixator device, which permits easy replacement of one holding device for another before and after imaging. It is recognized however that there has been a general shift in practice toward using internal distractor devices which are held in place with

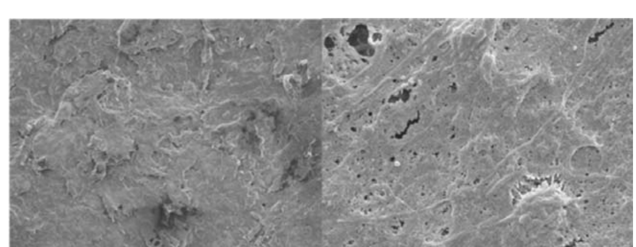

FIGURE 7. Scanning electron microscopy images showing the attachment and proliferation of MC3T3 cells on the surface of carbon fiber reinforced polyether ether ketone discs at 2 different magnifications.

integral mini-plates. Replacing these more complex designs with CFR-PEEK would require the entire device to be manufactured from this newer material. Further investigation is required to determine the feasibility of engineering such complex designs.

In conclusion, we have demonstrated the potential benefit of utilizing artifact free distraction pins and a temporary distraction device, which would permit enhanced sequential planning of mandibular advancements using 3D MRI techniques.

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