Title: A natural fibre reinforced composite material for multi-modal medical imaging and radiotherapy treatment

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Abstract

There is strong clinical need for a class of materials compatible with all common medical imaging modalities including Magnetic Resonance Imaging and X-Ray Computed Tomography which provide minimum attenuation to high intensity X-Ray photons used in Radiotherapy treatment, to improve patient outcomes and recovery times. In this work, we present a new natural fibre composite comprising wood pulp derived fibres embedded in polyester resin and bonded to expanded polystyrene cores. The resulting structure is demonstrated to have low visibility on Magnetic Resonance Imaging, X-Ray megavoltage imaging and Computed Tomography and to be less attenuating to radiotherapy photons than the commonly used carbon fibre or glass fibre reinforced composite materials. It is anticipated that this new material will facilitate improved radiotherapy planning and thus treatment outcomes.

Introduction

Modern radiotherapy practice involves comprehensive medical imaging including at a minimum Magnetic Resonance Imaging (MRI) and X-Ray Computed Tomography (CT) and ever more commonly Positron Emission Tomography (PET) to allow for accurate treatment [1]. Treatment commonly utilises Intensity Modulated Radiotherapy (IMRT) in which high intensity radiation is directed with variable intensities and patterns through a 360^{o} arc around the patient, building up high doses in the treatment region and minimising doses in surrounding tissue [2]. Optimum treatment efficacy and efficiency requires that the medical imaging be undertaken with the patient in a similar position such that the resulting treatment correctly targets only the volume of interest. Improvements have been made to the imaging protocols to best achieve this utilising similar flat patient support surfaces to those used for treatment, but to date there is not a material which is compatible with all imaging modalities and does not unduly attenuate the radiotherapy beam. A new composite material has been developed based on a wood pulp derived fibre which is suitable for use in patient support structures and which is compatible with primary imaging modalities and results in less beam attenuation than alternative materials, including the ubiquitous carbon fibre used for radiotherapy support structures.

Materials and Methods

Preparation of Natural Fibre Composite

The natural fibre composite is produced using a fibre derived from wood pulp, commercially available under the trademarks Tencel® or Lyocel®. A tightly woven sheet of this fibre ensures consistency and provides a high contact area between orthogonal fibres. The total ply needed for the skins are cut oversize, the first placed on top of a peel ply and hand rolled with Polyester resin (Resin in Styrene) mixed 30:1 with the hardener (MEKP, both components East Coast Fibreglass

Supplies, UK). For even ply, the next layer is oriented 90° to the one before and again hand rolled with the mixed resin. For odd total ply, a 45° oriented layer is included starting and finishing with a 0° or 90° layer. After the desired ply is reached, another layer of release film is applied before the whole layup is transferred to a pre-prepared vacuum bag including breather fabric layers, which is sealed and vacuumed until the resin is cured (12 hours). The skins are then adhered to 20mm thick extruded polystyrene core using a polyurethane impact adhesive.

Medical Imaging Compatibility Evaluation

Medical imaging compatibility assessment was undertaken with samples comprising 2, 3, 4 and 5 ply in each of the skins either side of the expanded polystyrene cores.

MRI was undertaken using the spine matrix of a 1.5T whole body MRI system (Avanto, Siemens, Germany). The incompatibility of materials for MRI typically stems from the presence of magnetic elements or conductive parts as is the case for carbon fibre. This can cause image distortion and localised heating as a result of eddy currents. In consequence, carbon fibre boards are not used in MRI systems [3]. The test samples were placed directly underneath a test object and imaging performed. Images of the test object are collected for no sample and the natural fibre, glass fibre and carbon fibre reinforced composites. The SNR is calculated using the sum of the signal intensity within a fixed region of constant size for all images and an equally sized region from the top left most corner of each of the images. The higher the SNR, the less the signal distortion and RF shading.

Compatibility with X-ray imaging is determined using the method which is most affected by material inhomogeneity, utilised for patient position confirmation, known as megavoltage imaging. Samples were placed as a cantilever over the edge of the movable patient couch in clinical linear accelerator (Elekta Versa HD) at 6MV and a dose of 1MU (0.01 gray at d_{max}) so only the sample of interest was imaged. A consistently sized region of these images was summed (proportional to the attenuation of the X-Rays) and the standard deviation calculated. The higher the homogeneity of the material, the lower the standard deviation. These values are minimised for the ideal material.

Radiotherapy Beam Attenuation Evaluation

For optimum radiotherapy treatment, there should be as little attenuation of the therapeutic radiation as possible. The patient support structure is cantilevered into the path of the radiation to minimise the presence of additional material. To determine the beam attenuation, the dose received in a detector behind the material (relative to the beam) is measured. The same linear accelerator as used for megavoltage imaging is used. The material under test was placed atop a solid water block (WT1 manufactured by Barts and The London NHS Trust, Tissue Equivalent Section, London, UK) encasing a cylindrical ionisation chamber dosimeter (Farmer® 2570, PTW, Germany). The linear accelerator provides a fixed quantity of radiation (6MV to a dose of 200MU over a 60x60mm treatment area) to the material under test. The accumulation of charge within the detector is proportional to the dose, which is calculated as a function of the skin ply. The attenuation due to a carbon fibre and a glass fibre reinforced honeycomb board was also determined for comparison.

Structural testing

The key structural properties of interest for a patient support material are flexural modulus and yield stress. A three point bend test [4] was used to determine these parameters. Samples with 50mm width are supported at a distance of 50cm on rollers and an increasing deflection applied while the applied force is measured. The resulting stress and strain values are used to determine the flexural modulus from the linear portion of the results while the yield stress is determined at the point at which the sample behaviour begins to deviate from linearity.

Results and Discussion

Medical Imaging Compatibility Evaluation

The results of the medical imaging compatibility tests are shown in Figure 1. For the MR imaging the left hand side of the figure shows that the reference value of air (at the same distance from the RF coil as the board samples) is found to be 52. A similar value is seen for the new natural fibre material demonstrating optimal performance. The glass fibre reinforced composite shows a small amount of RF shading at 49 but is significantly better than the carbon fibre at 17, representing a 67% reduction.

The megavoltage images on the right hand side of Figure 1 show that the natural fibre composite presents a homogeneity figure similar to the air measurement whilst the glass fibre composite is 56% worse, the carbon fibre beam attenuation is minimal.

These results suggest that the new material addresses the needs of a material for multimodal radiotherapy planning. Although there is some attenuation of the megavoltage x-ray in comparison to the carbon fibre, with a similar standard deviations this simply results in an easily removed offset, unlike the spatially variable RF shading caused by the carbon fibre in the MR images.

Radiotherapy Beam Attenuation Evaluation

The results of the radiotherapy beam attenuation are shown in Figure 2. Measurements of the attenuation due to the new natural fibre composite materials were performed on a limited number of samples owing to available materials and non-clinical time on the system. As such a wide range of ply was explored from 2 per side to 11 per side to provide a good range upon which to base the model fit. The error on the glass fibre and carbon fibre reinforced boards are shown as shaded regions. It is seen that according to the fit, the beam attenuation which would be anticipated due to 4 layers per skin would be 1.1% which is an improvement of over 30% in comparison to the ubiquitous carbon fibre.

Structural testing

The ideal material from a structural perspective presents with a high flexural modulus and failure stress meaning that significant forces are required to bend it in plane and ultimately cause failure. The results are presented in Figure 3 where it can be seen that although the maximum flexural modulus is provided by the 3 layer material, the 4 layer material has a higher failure stress and a flexural modulus only 10% lower. The honeycomb core of the glass fibre reinforced material allows it to outperform this material with 50% better failure stress and 20% better flexural modulus but the range of values which are found are within operational requirements and the improved performance in imaging and treatment outweigh the structural needs.

Conclusion

We have created and tested a novel material comprising natural fibre reinforced composite material encasing an extruded polystyrene core (NFC) which has been shown to outperform competitive materials such as glass fibre reinforced honeycomb cored composite (GFC) and carbon fibre reinforced composite (CFC) in terms of RF shading and distortion for MRI. The new material has similar performance to the CFC with regard to megavoltage imaging homogeneity and outperforms the GFC by 56%. It has poorer performance in structural testing, withstanding reduced stresses before deforming but still performs within required limits. Using this new material, a universal, multimodal patient support device which can be used in MRI, CT, megavoltage imaging and Radiotherapy can be produced improving patient outcomes.

Declaration of Interests

A patent has been filed (8080/5351/P/GB) for the natural fibre composite material. Medibord Ltd. declare a commercial interest.

Acknowledgments

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Figures

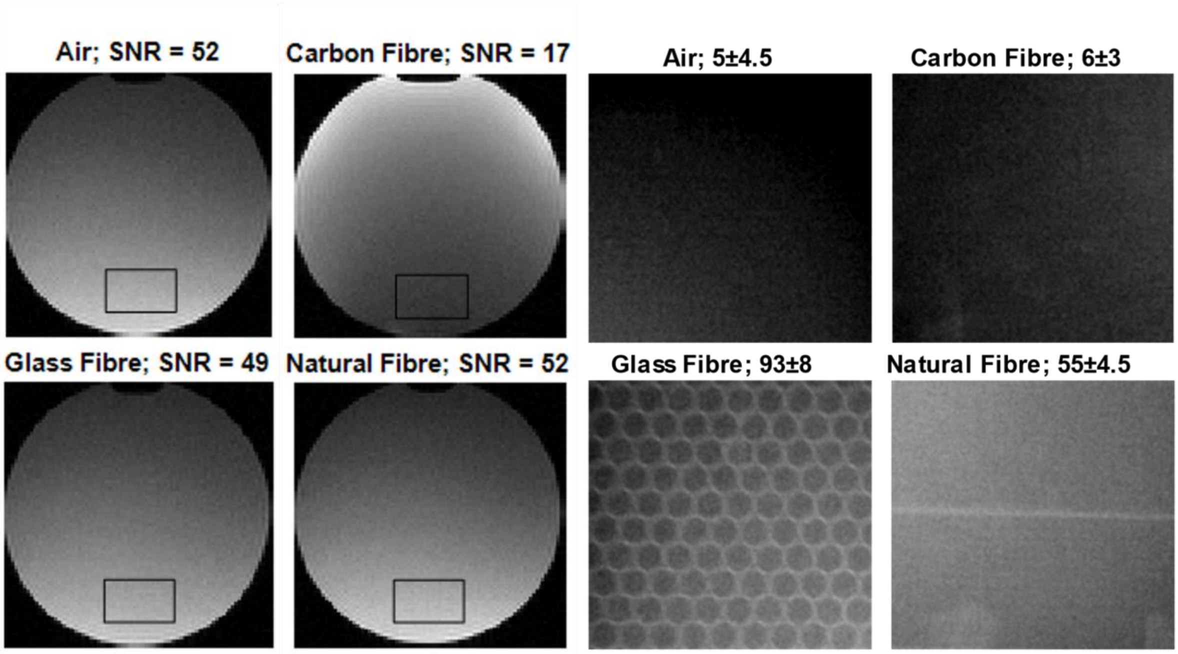

Figure 1. Imaging results for assessment of medical imaging compatibility. The four images on the left hand side are from MRI scans of the fluid filled test sample while the four images on the right hand side are from coronal Megavoltage Imaging. The right hand side images have been similarly contrast adjusted to maximise visibility in print and online. The left hand side images are all prepared with the same greyscale range.

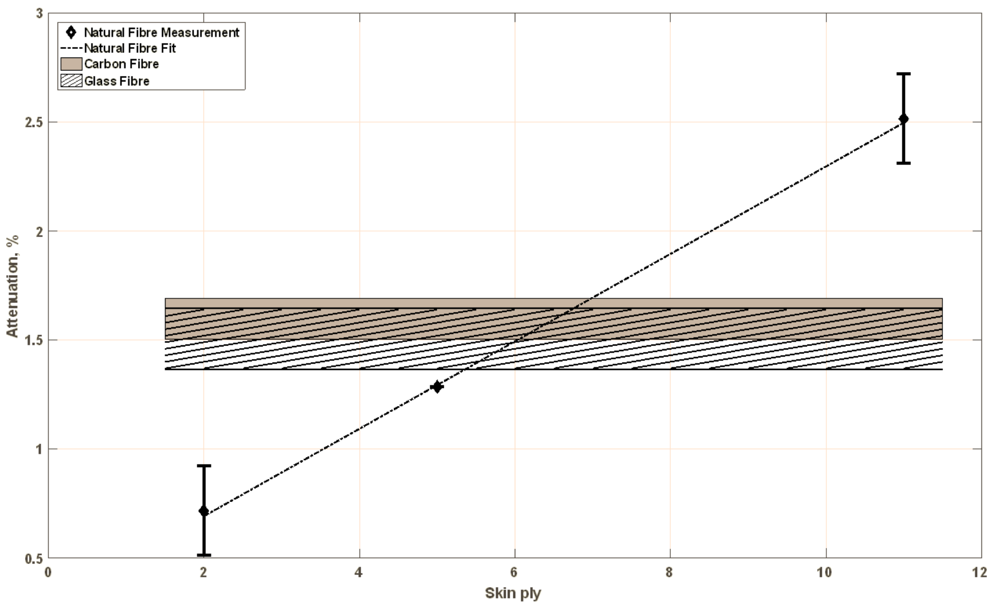

Figure 2. Plot of the radiotherapy beam attenuation caused by different materials. Hatched region represents carbon fibre grey area represents glass fibre reinforced composites. The linear fit is based upon the three data points shown. The equivalent attenuation for a 4 ply board is 1.09%.

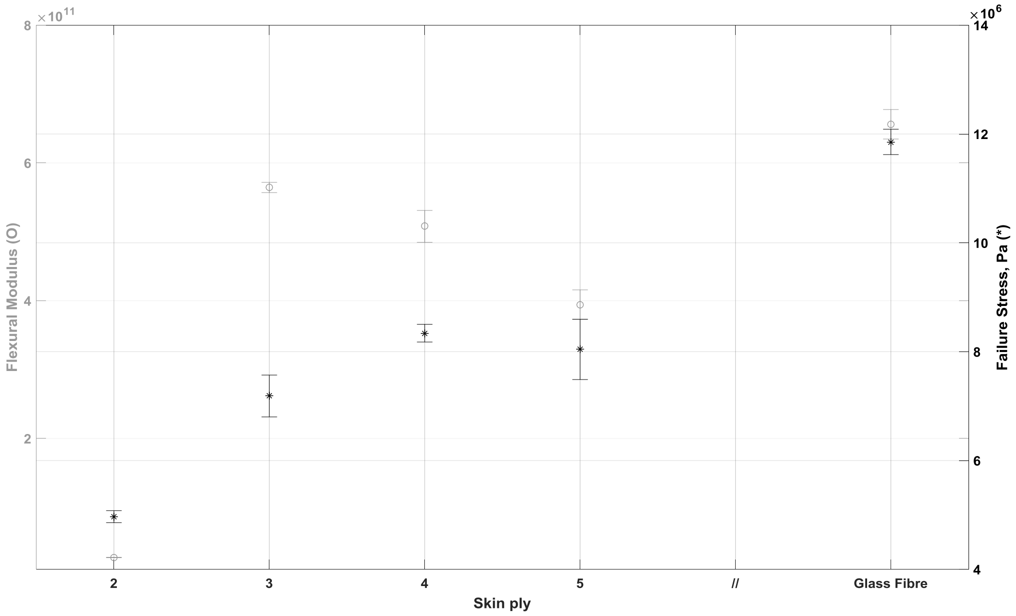

Figure 3. Structural testing evaluation. Flexural modulus in grey is at maximum for 3 ply approaching value of Glass Fibre Composite. Failure stress in black is at maximum for 4 ply but glass fibre honeycomb composite remains 65% higher.