Characterising Nanoporous Carbon Adsorbents for Biological Application to Chronic Kidney Disease

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The study characterises a range of advanced MAST carbons derived from pyrolysed porous phenolic resins for use in biological applications, considering how the porosity of the carbons impacts both the methods used to assess potential cytotoxicity and the removal of biological molecules relevant to kidney disease. The large surface area and pore volume available for adsorption make both the microporous and the mesoporous MAST carbons suitable for creatinine removal but not for removal of the small but highly water soluble urea. However, only the highly adsorbent MAST carbons with meso- and macroporosity were able to remove the high molecular weight inflammatory cytokine IL-6. It is the adsorption of the larger biological toxins, represented by IL-6 in this study and not removed by purely microporous carbons or in current haemodialysis therapy, which could most significantly contribute to the augmentation of current haemoperfusion therapy.

Keywords: Activated Carbon, Adsorbent, Chronic Kidney Disease, Uraemic Toxins.

1. INTRODUCTION

The large adsorptive potential of activated carbons makes them ideal for the removal of drugs and endogenous toxins from biological systems.1 Yatzidis first demonstrated the effective medical use of traditional carbons in an extracorporeal system for the treatment of renal failure in 1964.2 However, complications associated with fines release necessitated the coating of carbon with a biocompatible cellulose membrane.1, 4 The coatings provided a barrier that limited the size of biological molecules that could be removed and restricted the use of carbon adsorbents to the treatment of poisoning.1

There are a range of medical conditions which are influenced by the activity of microbial toxins and the associated excessive activity of endogenous inflammatory molecules whose uncontrolled activity is detrimental to human health.5–9 These toxins tend to be middle molecules larger than 500 Da in size and cannot be removed by traditional, microporous, coated carbons alone. However, new synthetic MAST carbons with a larger and more defined porosity are capable of removing these larger biologically active molecules by adsorptive processes into meso- and macroporous domains.10 MAST carbons offer a superior adsorptive potential for the treatment of medical conditions including sepsis, renal failure, liver failure and heart disease since complications associated with these disease processes often result from the build up and activity of larger, biologically active molecules which are not removed by current filtration based treatment strategies.

One application for adsorptive therapy is in the treatment of chronic kidney failure where new approaches to overcome the deficiencies in dialysis are necessary.11, 12 When renal failure occurs a large number of compounds normally excreted by the kidneys remain in the body. These substances, known as uremic retention solutes or uremic toxins if they are biologically active, are grouped into small water soluble compounds, middle molecules and protein-bound compounds.13 Haemodialysis removes some of the small water soluble toxins including creatinine and urea but fails to remove significant amounts of the protein bound and large molecular weight toxins particularly.14 The patho-physiology of progressive renal failure is linked to the effect which these poorly removed molecules have on body systems. Creatinine is a small water soluble guanidine produced by muscle breakdown
and is almost exclusively cleared by the kidneys. Urea is the
main product of nitrogenous compound metabolism
in the liver and its removal reflects efficient removal of
small ionic species such as potassium. While other ure-
emic retention solutes are emerging as more important indi-
cators of negative disease outcome, creatinine and urea
clearance rates may be used to assess the extent of kidney
disease and the efficiency of dialysis treatment. In addi-
tion the inflammatory cytokine IL-6 can be used to assess
the porosity required to remove larger molecular species.
These include the biologically active molecules that appear
to play a prominent role in the pathogenesis of inflamma-
tory disease.

The study describes the characterisation of a range of
synthetic medical grade, activated MAST carbon beads
and the way in which the tailored beads can be assessed
for use in biomedical applications, considering porosity,
cytotoxicity and the removal of model biological mark-
ers relevant to kidney disease. The unique porosity of the
meso- and macroporous MAST carbons themselves sug-
gest they are ideally suited as medical adsorbents. They
combine the superior adsorptive capacity of activated car-
bons with the specifically augmented capacity of MAST
carbons for larger biological toxins central to the patho-
physiology of disease states associated with dysregulated
inflammatory activation.

2. EXPERIMENTAL DETAILS

2.1. Carbons

Four types of medical grade, synthetic carbon bead with
varying porosity were synthesised by MAST Carbon Inter-
national (Guildford, Surrey, UK) from phenolic resin using
patented technology. The development of micropores is a
major contributor to surface area and was controlled by
physical activation burn-off using CO₂. Transport poros-
ity and the development of mesoporous and macroporous
domain size and volume was controlled by varying the
pore former concentration in the composition of pheno-
lic resin pre-cursor. A commercially available carbon
made from peach stone was included as a control (National
Academy of Sciences, Kiev, Ukraine).

2.2. Physical Characterisation

2.2.1. Scanning Electron Microscopy

The macroporous surface structure of the carbons was
visualised using a Jeol JSM-6310 scanning electron micro-
scope (SEM) set at an accelerating voltage of 5 kV. The
5 carbon samples were mounted on an aluminium stub fit-
ted with an adhesive carbon pad and sputter coated with
palladium using a Polaron SC7640 sputter coater.

2.2.2. Nitrogen and Mercury Porosimetry

The pore size distribution, pore volume and surface area
of the carbons was analysed using nitrogen gas adsorp-
tion at 77 K and mercury porosimetry on an Autosorp gas
sorption analyser and an automatic PoreMaster® mercury
intrusion porosimeter (Quantachrome Instruments) respec-
tively. The carbon surface area calculations were carried
out using BET theory.

2.3. Cytotoxicity Studies

2.3.1. MTS and LDH Assays

Carbon leachate was prepared by incubating heat sterilised
carbon samples in Dulbecco’s Modified Eagles Medium
(DMEM) for 24 hours using 10 ml media per gram of
carbon on a shaking incubator at 22 °C. A PVC polymer
coated with dibutyltin maleate was included as a posi-
tive cytotoxic control. The extracts were used undiluted or
diluted with an equal volume of media to give leachate
concentrations of 100, 50, 25 and 0%. V79 hamster lung
fibroblasts (ECACC no. 86041102) were grown in DMEM
supplemented with foetal calf serum (10% v/v) and incu-
becated at 37 °C in a 5% CO₂ atmosphere. Cells were pas-
saged by standard trypsinisation and seeded into 96 well
tissue culture plates at a density of 10⁴ cells per well. Cells
were incubated for 24 hours at 37 °C. Media was removed
and carbon leachate was added to the wells using serial
dilutions of 100, 50, 25 and 0% for each carbon leachate.
Cells were incubated for a further 24 hours. MTS reagent
(Promega) was diluted 1:5 in phenol red free media and
100 μl was added to each well. Plates were incubated
for 2 hours at 37 °C then absorbance was measured at
490 nm using a BioTek ELX800 spectrophotometer. The
LDH assay was carried out by setting up plates as for the
MTS assay. Following cell incubation with carbon leachate
for 24 hours cells were lysed and 50 μl of lysed cell
suspension was transferred to a second 96 well plate to
which 50 μl of LDH substrate solution was added. The
plates were incubated in the dark at room temperature
for 30 minutes. 50 μl of stop solution was added and
absorbance was measured as for the MTS assay. Assays
were carried out in triplicate. Results were analysed for
statistical significance using Students t-test.

2.3.2. Live/Dead Staining and Fluorescent Imaging

V79 cells were seeded into the wells of a 24 well plate at
a seeding density of 0.5 × 10⁴ cells per well and incubated
at 37 °C in a 5% CO₂ atmosphere for 24 hours. Media
was removed and carbon leachate was added to each well
in triplicate diluted by 50% in media. The cells were incu-
bated for a further 24 hours. Calcein acetoxymethyl ester
(calcein-am) was diluted 10⁴ in PBS. Media was removed
from the cells and 500 μl calcein-am solution was added
to each well. Plates were incubated for 20 minutes and solution was removed. Cells were rinsed with PBS and viewed by confocal microscopy. Calcein-am is cell membrane permeable and is hydrolysed to calcine by esterases in the cytoplasm of living cells. Calcein has a stable green fluorescence which can be monitored using excitation and emission spectra of 494 nm and 520 nm respectively.

2.4. Measuring the Removal of Model Biological Compounds Creatinine, Urea and Cytokine IL-6

2.4.1. Creatinine Adsorption

A standard curve was established for creatinine concentrations of up to 0.8 mM in Tyrode buffer. The kinetics of creatinine adsorption by the carbons was established by incubation of 30 mg of each of the test carbons in 5 ml of 0.8 mM creatinine solution over time following carbon equilibration in buffer for 24 hours. Samples were removed after 5, 30, 60 and 90 minutes and creatinine concentration remaining was measured by UV-spectroscopy at a wavelength of 245 nm in order to establish differences in creatinine removal by the carbons over time. The capacity of each of the test carbons for creatinine was measured by carbon incubation with different creatinine concentrations. 0.015 g of each carbon was incubated in 4 ml Tyrode buffer for 24 hours at 37 °C on an orbital incubator. Buffer was removed and each carbon was incubated in 5 ml of creatinine solution at concentrations of 0.5, 1, 2, 4, 6, 12, 16 mM for a further 24 hours. Carbon 2, 3, and 4 were also incubated in 20 mM and 30 mM creatinine solution. Following incubation with the carbon samples creatinine solutions were removed and analysed by UV-spectroscopy at a wavelength of 245 nm. The amount of creatinine absorbed per gram of carbon was calculated according to the following equation.

\[ q_e = \frac{V(C_0 - C_c)}{m} \]

\( q_e \) is the amount of adsorbate per gram of carbon at equilibrium, \( C_0 \) is the initial concentration of creatinine, \( C_c \) is the concentration reached, \( V \) is the volume of solution \( L \) and \( m \) is the amount of carbon added in grams.

2.4.2. Urea Adsorption

Urea concentration was measured according to a previously established method by the reaction outlined in Figure 1.\(^\text{10}^\) The adsorptive capacity of the test carbons for urea was measured by incubating 5 different concentrations of urea (1, 3, 5, 10, 15 mM) made up in Tyrode buffer with 0.025 g of each test carbon for 24 hours at 37 °C on an orbital incubating shaker. The concentration of urea was measured by mixing 15 µl of urea sample with 75 µl of a 10 mg ml\(^{-1}\) urease solution made up in 40 mM HEPES buffer. 1 ml of phenol nitroprusside solution was added followed by 1 ml of hypochlorite reagent and then 5 ml of water. The solution was incubated for 30 minutes at 37 °C. Absorbance of the solution was measured at a wavelength of 625 nm using UV-spectrometry. All tests were carried out in triplicate and the amount of urea removed per gram of carbon was calculated as for creatinine.

2.4.3. IL-6 Adsorption

Mast carbons 1, 3, and 4 were used to assess the effect of pore size distribution on the kinetics of cytokine IL-6 removal over time. 0.1 g of each carbon was weighed into eppendorf tubes in triplicate and 1 ml of phosphate buffered saline was added. Carbons were incubated for 1 hour on an orbital shaking incubator at 25 °C. PBS was removed and 1 ml of human plasma spiked with 1000 pg ml\(^{-1}\) IL-6 was added to each carbon sample. The samples were incubated at 37 °C on an orbital incubating shaker and 220 µl aliquots were removed at time points of 5, 45, 60 and 90 minutes. IL-6 concentration remaining in the plasma samples was measured using an IL-6 ELISA kit (BD Biosciences) according to manufacturer’s instructions. A 1 in 5 dilution of samples was carried out in order to calculate IL-6 concentrations from the recombinant IL-6 standard curve. All data was analysed for statistical significance using Students t-test.

\[
\begin{align*}
\text{Urea} & \quad + \quad \text{H}_2\text{O} \quad \xrightarrow{\text{urease}} \quad 2\text{NH}_3 + \text{CO}_2 \\
\text{NH}_3 & \quad + \quad \text{OCl}^- \quad \xrightarrow{\text{sodium nitroprusside}} \quad \text{indophenol} \\
\end{align*}
\]

Fig. 1. The reaction of urea catalysed by urease forming ammonia which in turn reacts with phenol and hypochlorite to indophenol in the presence of sodium nitroprusside.
3. RESULTS

3.1. SEM

The MAST carbon beads have a uniform, spherical shape with a diameter of 250 to 500 μm (Fig. 2). The beads have a compact surface structure and larger surface macro-pores are not visible in contrast to the control carbon. The highly porous internal structure of the MAST beads can be seen in the higher resolution image of the transected bead. In contrast the carbon control made from peach stone has a much larger granular size and a more angular, non-uniform shape. For biological applications the consistent, smooth, spherical nature of the MAST carbon beads is important because it improves biocompatibility. Haemolysis and blood cell activation are less likely.

![Fig. 2. SEM images of (a). MAST carbon bead 2 (×400), (b). MAST carbon bead 2 (×40) (c). control carbon (×40).](image)

3.2. Porosimetry

The gas nitrogen adsorption isotherm (at 77 K) for MAST carbon 1 shows a type I Langmuir isotherm (IUPAC classification) indicative of micropore filling (Fig. 3). MAST carbons 2, 3 and 4 produced type IV adsorption isotherms characteristic of mesoporous carbons. Table I contains the porosimetry data for synthetic MAST carbons 1 to 4 and the control carbon 5. The peach stone derived carbon 5 has the lowest calculated surface area of 992 m² g⁻¹. Its pore volume is 0.56 g cm⁻³ which is almost a quarter of the pore volume of the highly mesoporous MAST carbon 2. Carbon 1 has the lowest pore volume and the highest density of the MAST carbons and is purely microporous with all pores less than 2 nm in diameter. Carbon 2 has the highest pore volume of 2.1 cm³ g⁻¹, predominantly in the area of small macropores, and has a large surface area of 1483 m² g⁻¹. Carbon 3 has some smaller mesoporous domains with an average diameter of 30 nm, a large surface area of 1465 m² g⁻¹ but a lower pore volume of 1.3 cm³ g⁻¹. Carbon 4 has a lower pore volume and surface area than carbon 2 (1236 m² g⁻¹ and 1.61 cm³ g⁻¹ respectively) but additionally has larger meso-macroporous domains with an average pore diameter of 120 nm.

3.3. Cytotoxicity Studies

The MTS assay can be used to measure the potentially negative effect of carbon leachate on cell growth since the MTS tetrazolium compound is bioreduced by dehydrogenase enzymes in metabolically active cells into a formazan product which can be measured colorimetrically.

![Fig. 3. Nitrogen adsorption isotherms for MAST carbons 1 to 4.](image)
at 490 nm using a plate reader. A reduction in signal indicates an adverse effect on cell growth. Conversely, the LDH assay is used to measure cell death in response to carbon leachate exposure by the enzymatic conversion of a tetrazolium salt to a red formazan product, which is released into the cell medium following cell lysis. An increase in signal indicates an increase in cytotoxic effect. Cells grown for 6 hours in media that was pre-incubated with the test carbons for 24 hours showed no significant change in normal cell activity compared to those grown in standard media alone (Fig. 4(a)). However, for the MAST carbons with the greatest adsorbent capacity cell metabolic activity significantly declined following 24 hour incubation with 100% carbon pre-conditioned media (Fig. 3(b)). The reduction in cell metabolic activity measured by reduced MTS absorbance was not observed for control carbon 5. Following 50% dilution of pre-conditioned media with normal media cell metabolic activity returned to control levels suggesting that the carbons remove media nutrients from the media so that cell growth cannot be sustained in 100% carbon conditioned media for 24 hours. The observed reduction in cell metabolic activity is not an indicator of carbon cytotoxicity but an indicator of the large adsorptive capacity of the test MAST carbons. In contrast, the cytotoxic control media pre-conditioned in tin maleate reduced cell activity to less than 10% even following 50% dilution with normal media prior to addition to the cells. Further cytotoxicity assays were carried out in carbon conditioned media diluted by 50% with normal media. Cells grown for 6 hours and 24 hours in carbon pre-conditioned media diluted with 50% normal media showed no change in activity indicating no leaching of cytotoxic components from the carbons into the media (Fig. 4(a)). In contrast, after 6 hours incubation in tin maleate conditioned media cell activity had reduced to 60% that of the control cells and after 24 hours growth was reduced to 10% that of the controls. The LDH assay showed a similar result (results not shown). Fluorescent staining of live cells with calcein-am at 2, 4, 6 and 24 hour time points also showed comparable cell growth for cells grown in media pre-incubated with carbon and those grown in regular media (Fig. 5). In contrast the cells grown in tin maleate pre-incubated media showed a progressive reduction in cell number over time.

### 3.4. Creatinine Removal

A linear relationship between absorbance and creatinine concentration was observed between concentrations of 0.01 mM and 0.8 mM \((r^2 = 0.99)\) allowing calculations of unknown concentrations of creatinine to be calculated within this range. The adsorption isotherms for carbon 1 to 4 were not significantly different from one another and indicated a high removal capacity for creatinine (Fig. 6(a)). Carbons 1 to 4 removed up to 2.5 mMol per gram of carbon and reached saturation capacity at 16 mM creatinine. Carbon 1 had a lower capacity for creatinine removal than carbons 2 to 4. Peach stone derived carbon 5 reached saturation at a concentration of 8 mM creatinine and had a much lower removal capacity of 1 mmole of creatinine per gram of carbon. MAST carbon 2 and 4 showed the fastest removal kinetics over 90 minutes incubation of carbon in 0.8 mM creatinine solution adsorbing 0.1 mmoles per gram of carbon (Fig. 6(b)). All of the mast carbons removed significantly more creatinine than peach stone derived carbon 5.

### 3.5. Urea Removal

A linear relationship between indophenol absorbance and urea concentration was observed between concentrations of 0.2 mM and 40 mM urea \((r^2 = 0.99)\). The adsorption isotherms for each of the carbons showed limited removal of urea following incubation of the carbons in increasing
concentrations of urea (Fig. 7). Only at the highest concentration of 15 mmoles per gram of carbon was any significant difference seen in removal of urea by carbon 5 and the other carbons. Carbon 5 reached saturation point at a concentration of 10 mM urea. Carbons 1 to 4 did not reach saturation point at the highest urea concentration used and removed 0.15 mmoles per gram of carbon at 15 mM urea concentration.

3.6. IL-6 Removal

No removal of IL-6 was observed by carbon 1 (Fig. 8). Carbon 4 rapidly removed the majority of IL-6 after only 5 minutes incubation with IL-6 spiked human plasma. In contrast, adsorption of IL-6 by carbon 3 was much slower and the concentration of IL-6 was reduced by only 100 pg ml$^{-1}$ following 90 minutes incubation with spiked human plasma.

4. DISCUSSION

The ability of activated carbons to remove a wide range of biological molecules by adsorption depends on the properties of both the carbon adsorbent and the biological medium. Factors such as carbon particle size, surface area, pore size distribution, pore volume, surface chemistry and the competing properties of other salts and proteins present...
in solution will impact both the adsorptive rate and capacity for removal. In addition the adsorptive power of the carbons themselves may influence the methods routinely used to assess the appropriate use of carbons for medical applications. The study sought to model the way in which the properties of advanced MAST carbons can be assessed for suitable use in medical adsorbent systems, taking into account the impact of the adsorptive capacity of the carbons themselves on the test procedures employed and material properties which must be modified for biological significance. The use of a synthetic polymer based precursor material allows the production of activated carbons with a homogeneous and reproducible porous structure unlike that observed using natural precursor materials. MAST activated carbons also possess unique porosity compared to other activated carbons. These are obtained using novel adaptations of phenolic resin technology to produce high Novacarb based synthetic mesoporous carbons of medical grade quality.\textsuperscript{17,18}

The study compared the adsorptive capacity of four advanced, phenolic resin derived MAST carbons with different surface areas, pore size distribution and pore volume with that of a traditional carbon derived from peach stone. In addition, standard cytotoxicity measurements were adapted in order to take into account the impact of carbon adsorptive capacity on the interpretation of results obtained.

The potential cytotoxicity of the carbons was measured using standard MTS and LDH assays adapted from the European international standard procedures for biological evaluation of medical devices part 5 (EN ISO 10993-5). The standard assay requires incubation of potential biomaterials in media for 24 hours prior to exposure of leachate to cells for 24 hours. However, when the MAST carbons were used in this way cell growth was not sustained over the 24 hour time point in comparison to the media only and traditional carbon control. Dilution of leachate with normal media by 50% removed this effect in contrast to the cytotoxic control. The results indicated that the carbons with a large adsorptive capacity were removing the media nutrients rather than having a cytotoxic leaching effect causing reduced cell metabolism on exposure times of greater than 6 hours. In order to allow for this effect a number of adaptations to the assay are possible. The cell exposure time could be reduced to 8 hours in order to reduce the impact of nutrient removal by the carbons. However, the effect of the cytotoxic positive control was reduced more substantially than when leachate was diluted by 50% and cell exposure was maintained at 24 hours, suggesting that dilution and maintained 24 hour exposure time was a better adaptation of the assay. The results of the assay were verified using fluorescent staining of live cells at different time points during incubation with carbon pre-conditioned media. A qualitative increase in cell number was observed over the 24 hour incubation for each of the carbons but not for the cytotoxic control. The results demonstrate the importance of using a range of complementary assays to allow accurate interpretation of results since at first glance the results suggest a cytotoxic leaching effect by the MAST carbons on 24 hour cell exposure. In fact the effect is due to the powerful adsorptive capacity of the MAST carbons themselves in confirmation of results previously obtained showing protein and ion adsorption from cell media by MAST carbons.\textsuperscript{19}

The removal of creatinine over 90 minutes occurs more rapidly on incubation with carbons 2 and 4 but is significantly greater for all of the carbons 1 to 4 than for control carbon 5. The combined large surface area and pore volume influence removal characteristics most significantly in this case. Creatinine is a small molecular weight, aromatic, water soluble compound of 113.12 Da with a normal plasma concentration of 0.11 mM. Uremic patient levels can rise to 1.2 mM and the experimental results indicate that MAST carbons, with a capacity to remove 2.5 mmoles g\textsuperscript{-1} of carbon, could remove clinically significant levels of creatinine in an adsorbent system. Data indicating removal from human plasma is necessary to substantiate the results as removal was measured from Tyrode buffer solution. Additionally, the production of creatinine oxidative metabolite creatol by catalytic oxidation of creatinine on the surface of carbon has been reported in the literature. Creatol is rapidly converted to methylguanidine, a uremic toxin known to accumulate in end stage renal failure.\textsuperscript{20,21} Measurement of carbon removal of creatinine by adsorption may be augmented by catalytic conversion of creatinine suggesting caution in the interpretation of removal data prior to confirmation of additional breakdown products in solution. Care should also be taken when interpreting biological data since catalysis, as well as adsorption, may contribute to the apparent observation of removal.

Urea removal by all of the carbons was poor. Urea is a small molecular weight molecule of 60.06 Da but is highly water soluble and so remains in solution rather than bound to the hydrophobic carbon surface. Since clinical levels reach 40 mM in uremic patients it is unlikely that carbon removal of urea by adsorptive processes will prove clinically useful.

It may be possible to improve urea removal by the introduction of surface acidic groups since urea may then bind to the negatively charged surface. Devices such as the REDY sorbent system deal with urea removal using a urease layer to convert urea to ammonia and carbon dioxide followed by ammonia adsorption by a cation exchanger, zirconium phosphate.\textsuperscript{22}

While creatinine and urea are useful markers when assessing removal strategies relevant to the treatment of renal failure they represent only small water soluble molecules which are readily removed by dialysis and are not considered to be particularly toxic. Of more importance are the larger molecular weight and protein bound
uremic toxins which are poorly removed by current dialysis strategies and are known to have a significant impact on cardiovascular damage associated with renal disease.\textsuperscript{23} The current study used the cytokine IL-6 as a representative large molecular weight inflammatory protein of 26 KDa in order to assess the use of MAST carbons in the removal of these more clinically relevant group of molecules. The results indicate rapid and sustained removal of IL-6 by the mesoporous carbon 4. An 85\% reduction in IL-6 concentration occurred following 5 minutes incubation of spiked plasma solution with carbon 4. In contrast, very little removal occurred on incubation with carbon 3 with only a 30\% reduction in IL-6 concentration over the 90 minute incubation time. The purely microporous carbon 1 showed no removal of IL-6 over the time course of the experiment. The results indicate the importance of larger mesoporous and small macroporous domains in the removal of larger biologically active molecules as observed in previous blood perfusion studies with carbon based adsorbents.\textsuperscript{10}

5. CONCLUSIONS

The study characterises a range of polymer pyrolysed advanced MAST carbons for use in biological applications, considering how the porosity of the carbons impacts both the methods used to assess potential cytotoxicity and the removal of biological molecules relevant to kidney disease. The large surface area and pore volume available for adsorption make both the microporous and the mesoporous MAST carbons suitable for creatinine removal but not for removal of the small but highly water soluble urea. However, only the highly adsorbent MAST carbons with meso- and macroporosity were able to remove the larger molecular weight cytokine IL-6 suggesting their application in the further development of adsorbent systems to augment haemodialysis therapy. Activated carbons currently in use for medical applications do not possess porous domains larger in size than micropores and small mesopores. The study introduces activated carbon beads with uniquely tailored meso- and macro porous domains capable of removing larger biological toxins. The capacity of the beads for poorly removed larger toxins could revolutionise the use of adsorptive technology in medical haemoperfusion and dramatically reduce associated complications for patients on renal, hepatic and cardiac directed perfusion systems.

References and Notes

2. H. Yatzidis, A convenient haemoperfusion micro-apparatus over charcoal for treatment of endogenous and exogenous intoxication.


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