Characterization of Zirconium-Based Material (ZBM) Synthesized by Gradual Drying for Molybdenum-99 (99Mo) Adsorbent

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Abstract. Technetium-99m (99mTc), the daughter radionuclide of Molybdenum-99 (99Mo), is the most widely used radionuclide in the world and predicted to face a shortage in the future. A Zirconium-based material (ZBM) is an alternative solution to overcome this problem due to its high adsorption capacity toward 99Mo, and ability to release 99mTc. The performance of the ZBM is influenced by its material properties, especially the surface area and pore diameter. This study aims to characterize and evaluate the ZBM developed by new synthesis method. The ZBM was synthesized using zirconium(IV) chloride, 2-propanol, water and tetrahydrofuran. The drying process after synthesis was conducted by gradual heating. The resulting material was analysed by XRD, SEM, and BET method. The 99Mo adsorption and 99mTc releasing capacity was also evaluated. The analysis result shows that the ZBM is an amorphous material, while its surface area, pore volume, and pore diameter was 45.8 m²/g, 0.19 cm³/g, and 16.29 nm, respectively. The 99Mo adsorption, and 99mTc releasing capacity of the ZBM was 181.58 mg Mo/g ZBM, and 91.81%, respectively.

Keywords: ZBM, 99Mo, 99mTc, column chromatography

1. Introduction

Technetium-99m (99mTc) is the most widely used diagnostic radionuclide around the world due to its short half-life, low and pure gamma energy, as well as easy to use in generator technology [1]. Because of its ability to bond a broad spectra ligand, 99mTc can be labelled into many kind of existing radiopharmaceutical kits. Furthermore, new 99mTc-based radiopharmaceuticals are still developed for new diagnostic methods in nuclear medicine [2].

99mTc is the daughter radionuclide of Molybdenum-99 (99Mo), which is usually produced from Uranium-235 (235U) [3]. This production route generates a high specific activity fission Mo-99, which barely contains non-radioactive molybdenum. The separation process of the fission 99Mo and 99mTc is conducted by column chromatography method using alumina, which has an adsorption capacity to molybdenum of 20 mg Mo/gram. The alumina column will retain the fission 99Mo, while the 99mTc can be eluted using saline solution every 24 hours until the 99mTc activity is too low to be eluted[4].

The dependence to the fission 99Mo drove nuclear medicine to face fission 99Mo crisis in 2009 due to the shutdown of two main reactors in Netherland and Canada [5]. Furthermore, the ageing of the reactors producing fission 99Mo around the world causes the concern on the possibility of the fission 99Mo shortage in the future. The other concerns are the high amount of radioactive waste resulted from separation process of fission 99Mo and another fission product of 235U, as well as the sophisticated facility...
for the post-irradiation process. These encouraged many researchers to find alternative routes on $^{99}$Mo production. Several methods have been developed such as cyclotron-based $^{99}$Mo production [6–8] and neutron irradiation of natural molybdenum [9]. The cyclotron-based route is predicted as a promising method due to the presence of cyclotron in many hospitals and research center around the world. However, this method demands $^{100}$Mo as an irradiation target [10, 11] which is very expensive. The natural molybdenum production route has been developed in several countries. This needs an inexpensive irradiation target, simple post-irradiation product, and very low radioactive waste. The main drawback of this production route is the lower specific activity (LSA) of the resulting $^{99}$Mo.

The specific activity of natural $^{99}$Mo is too low to be applied on alumina-based column chromatography, therefore another separation method is required. Several separation methods have been developed as follows: solvent extraction [12], column extraction [13], precipitation [14], sublimation, electrochemical separation and column chromatography [15]. The last-mentioned method is preferable due to its possibility to be developed as a simple generator package. The column chromatography method requires a material which can adsorb $^{99}$Mo and release $^{99m}$Tc during elution and several materials have been proposed for the LSA $^{99}$Mo [16, 17], one of them is zirconium-based material (ZBM) [18].

The ZBM has been developed for almost a decade and proposed as the substitution of alumina in column chromatography. It has adsorption capacity to molybdenum up to 180 mg Mo/gram ZBM and sufficient hardness as column material. The material has been also developed as generator package which is evaluated its performance [19]. The ZBM will be a promising material for column chromatography, however, this material still has a drawback on improving the $^{99m}$Tc yield. It is obvious that the application of NaOCl solution in the chromatography column can increase the yield [20]. However, the presence of trace amount of NaOCl in the eluted $^{99m}$Tc solution is able to interfere with the radiolabeling process. Therefore, the synthesis process of the ZBM still needs to be improved. In this study, the gradual heating process in the synthesis of the ZBM was applied to improve its characteristics and performance as adsorbent material.

2. Method
A solution of $^{99}$Mo was obtained from Center for Radioisotope and Radiopharmaceutical Technology, National Nuclear Energy Agency. The chemicals used in this study were all analytical grade and supplied by Merck. These includes zirconium chloride ($\text{ZrCl}_4$), 2-propanol, tetrahydrofuran (THF), tetraethyl orthosilicate (TEOS), NaOH, NaOCl and HCl, they were used without any further purification. Purified water was obtained from IPHA Laboratory.

The synthesis method of the ZBM has been described elsewhere [19]. The gradual drying process was carried out immediately after the wet mass of ZBM was obtained. The drying process was performed at 4 steps up to 120°C. The resulted ZBM was analyzed its morphology, phase composition, and porosity using a FESEM Hitachi SU-8000, Rigaku RINT 2500X diffractometer, and Belsorp Mini II sorption system at 77 K, respectively. A $^{99}$Mo adsorption and $^{99m}$Tc elution experiment of the ZBM has been described elsewhere [19].

3. Result and Discussion
The ZBM is actually developed from poly zirconium compound with several modifications [21]. This material mainly consists of Zr, O, and Cl for adsorption process, as well as Si coating for increasing its hardness. As described by Awaludin et al., the adsorption mechanism is based on ion exchange between Cl$^-$ and $^{99}$MoO$_4^{2-}$. The decayed $^{99m}$TcO$_4^-$ is released from the material after being replaced by Cl$^-$ from the saline solution [18]. It is predicted that the adsorption capacity is influenced by the surface area of the material, whereas the ability to release $^{99m}$Tc is still unknown. In this study, a new drying process is developed, as well as its influence on the material characteristics, its adsorption capacity to molybdenum, and its ability to release $^{99m}$TcO$_4^-$. The morphological characteristic was evaluated, and its result is presented in Figure 1.
Figure 1. SEM images of the synthesized ZBM.

Figure 1 shows that the ZBM tends to form big clusters, and this was identical with the ZBM without gradual drying synthesized by Saptiama, et al [19]. This might be caused by the Si-coating, however, this still likely possesses an adequate amount of pores on its big cluster. This big cluster might play an important role to ensure that the column chromatography is easy to be eluted. On the other hand, the smaller particle might cause the column is banged up. The ZBM, without Si-coating, tends to swell during the adsorption process making the elution process is impossible. It is obvious that the Si-coating play an important role to keep the original form of the ZBM, even though its amount is no more than 6.1% [18, 19].

The XRD pattern is analyzed to evaluate the ZBM’s phase composition, while its purity is unable to be evaluated due to the absence of the standard. The resulted XRD pattern, as shown in Figure 2, revealed that the ZBM is an amorphous material, which is might be caused by an inadequate drying temperature to form crystalline material. This is the main difference of the ZBM with other 99mTc/99Mo separation materials, which are mostly a crystalline material [22]. In addition, this material possesses a polymer structure consisting of zirconium and oxygen as its main chain [18, 19].

Figure 2. XRD pattern of the ZBM.
N$_2$ adsorption-desorption isotherms of the ZBM, as shown in Figure 3, is type IV. This means the ZBM is a mesoporous material [17]. Most of the $^{99}$Mo/$^{99m}$Tc separation materials are mesoporous, which might play an important role in $^{99}$Mo adsorption [17, 23–26]. The ZBM’s SBET was 45.80 m$^2$/g which is lower than mostly $^{99}$Mo/$^{99m}$Tc separation materials, whereas the pore diameter and pore volume was 16.30 nm and 0.19 cm$^3$/g, respectively.

![Figure 3. N$_2$ adsorption-desorption isotherms, and pore-size distribution of the ZBM.](image1)

The ZBM was then performed as $^{99}$Mo/$^{99m}$Tc column chromatography material. A 5087 GBq of $^{99}$Mo was adsorbed into the ZBM, and 90.12% of $^{99}$Mo was absorbed. The calculated adsorption capacity was 181.58 mg Mo/g ZBM. This value was higher than mostly $^{99}$Mo adsorbent material [17, 22–26]. After $^{99m}$Tc growth, this radionuclide is eluted with saline solution and the result is presented in Figure 4.

![Figure 4. $^{99m}$Tc elution profile in column chromatography based on ZBM.](image2)

Figure 4 shows that high activity of $^{99m}$Tc was found in fraction 2-5. This was very beneficial for the generator development because a high amount of activity can be obtained in 4–5 mL of eluate and the $^{99m}$Tc yield was 91.81%. Moreover, this can produce high radioactivity concentration of eluate which is very important for radio labelling of several radiopharmaceutical kits. However, the NaOCl solution is

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**Figure 3.** N$_2$ adsorption-desorption isotherms, and pore-size distribution of the ZBM.

**Figure 4.** $^{99m}$Tc elution profile in column chromatography based on ZBM.
still demanded to release the $^{99m}$Tc from the column. The presence of NaOCl as an oxidizing agent might decrease the effectivity of reducing agent in radiopharmaceutical kit [27]. Therefore, there is a need to find another way to replace the NaOCl’s role.

4. Conclusion
The ZBM has been synthesized with a new method and its property has been characterized. There was no significant difference of characteristics and adsorption capacity between this ZBM with the previous one. The $^{99m}$Tc yield of this ZBM is higher than the previous one, even though a NaOCl solution was still used.

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