# Ion-Imprinted Polymer Concept for Selective Extraction of $^{90}$Y and $^{152}$Eu for Medical Applications and Nuclear Power Plant Monitoring

Pascal Froidevaux*, Steffen Happel[a] and Anne-Sophie Chauvin[§b]
[§]SCS Poster Prize Winner

*Abstract:* The metal ion imprinted concept has been used to imprint dipicolinic derivative coordination cages in styrene-based polymeric material. This resin displays very high selectivity for yttrium and lanthanides. Distribution coefficients determined for $^{88}$Y and $^{85}$Sr emphasize the possibility for the material to be used as chromatographic support for direct production of medical grade $^{90}$Y from a $^{90}$Sr source. Europium has been successfully extracted by the resin from a large volume of tap water. Thus the material could be used for radiation monitoring of nuclear power plants, particularly regarding the determination of radiolanthanides in the cooling system.

**Keywords:** Europium · Extraction · Ion imprinting · Lanthanides · Yttrium-90

## Introduction

The concept of molecular-imprinted polymers was introduced more than 20 years ago by the groups of Wulff and Mosbach [1][2]. Molecular imprinting is a procedure which can be applied to a wide range of targeted molecules. In this technique, suitable polymerizable binding groups are linked to a template molecule that is copolymerized in the presence of a cross-linking agent to form a cross-linked polymer. Further removal of the template leaves binding sites with the shape corresponding to that of the template [3]. Many applications have been reported for the selective recognition and separation of organic compounds [4] but less attention has been paid to the use of molecular-imprinted polymers for the separation of inorganic ions. However as early as 1976, Nishide and Tsuchida reported on the selective adsorption of metal ions on cross-linked polyvinylpyridine resin prepared with a metal ion as template [5]. Recently Murray and Southard reviewed the latest issues on metal ion selective molecularly imprinted material [6]. Current methods for making molecularly imprinted metal ion complexing polymers are described. One of the main requirements for successful polymer–cation recognition is the selection of the appropriate monomers of the ion-ligand association. The stability constant of the metal-ion complex is therefore a crucial parameter. Inclusion of one or more polymerizable substituents to the ligand requires synthetic procedures that should be kept as simple as possible. Most imprinted resins are made using free radical polymerization, thus requiring ligands bearing a vinyl or an allyl substituent. For instance, using a vinylbenzoate uranyl complex in a polymer synthesis involving styrene and divinylbenzene, Kimaro *et al.* [3] obtained a polymer with promising properties for the selective extraction of uranyl cations. In parallel Lemaire and co-workers [7] were able to prepare a polymer with increased selectivity for $Gd^{3+}$ over $La^{3+}$ by using monomers synthesized from DTPA derivatives with vinylaniline moieties. Using similar strategies of isolating monomer complexes of lanthanides with vinylaniline derivatives of EDTA and DTPA, Vigneau *et al.* [8] obtained an imprinted polymer with enhanced lanthanide extraction capacity. Murray and Southard also reported two main approaches in the creation of an ion-selective imprinted polymer [6]. In the first one the ligand monomer is a vinyl-substituted ligand with coordination groups that will be eventually attached to a supramolecular polymeric support. The second approach consists in using a vinyl-derivative of macrocyclic ligand that already has the geometric constraints predisposed to a certain metal ion. The imprinting process is then used to make small changes in the geometry, in order to enhance the selectivity. This macromolecular arrangement favorable for ion sorption on polymeric sorbents was successfully used by the groups of Chen, Kabanov, and Efendiev [9].

While metal ion selective molecularly imprinted materials became more and more devoted to extraction or analysis of transition metal ions, few attempts were made to obtain polymers with enhanced selectivity for the lanthanides series. In contrast to transition metal ions, cations of the lanthanide series have very similar chemical properties and high coordination number (N = 6–10). Thus separation of Ln(iii) cations is a difficult task and every improvement in this field is welcome. Environmental analysis of lanthanides and the parent yttrium cations

*Correspondence:* Dr P. Froidevaux
University of Lausanne
Institute of Applied Radiophysics
Grand Pré 1
CH-1007 Lausanne
Tel.: +41 21 623 34 80
Fax: + 41 21 623 34 35
E-Mail: pascal.froidevaux@chuv.ch
[a]Campus de Ker Lann
Parc de Lormandière
Rue Maryse Bastié - Bât. C
35170 Bruz, France
[b]Laboratory of Lanthanide Supramolecular Chemistry
Ecole polytechnique fédérale de Lausanne
BCH 1402
CH-1015 Lausanne

is not a priority but when their radioactive isotopes are considered, it becomes obvious that development of analytical methodology to separate radiolanthanides and $^{90}$Y is a prerequisite to any environmental radioactivity survey program: $^{90}$Y is the daughter product of the very radiotoxic calcium-analog $^{90}$Sr radionuclide that can be incorporated by humans through the dairy food chain. Due to its hard β-emission and short half-life ($t_{1/2}$ = 64 h, $E_{\beta max}$ = 2.3 MeV) $^{90}$Y analysis is often preferred to the analysis of $^{90}$Sr [10]. Radiolanthanides have the highest production yield of all the radioisotopes produced by the fission of $^{235}$U. Thus any good nuclear power plant monitoring program should be able to extract $^{152}$Eu from cooling system and environmental samples for very sensitive gamma-emitter analysis. Moreover recent developments in nuclear medicine require improvement in the availability of very pure radiolanthanides [11] and $^{90}$Y in a nuclear medicine laboratory. For instance radiosynovectomy is now a well accepted therapeutic procedure for palliative treatment in inflammatory joint diseases [12] requiring $^{90}$Y as hard β-emitter. Radiolabelling of target molecules with $^{90}$Y for tumor currietherapy will increase the need to separate $^{86}$Y from cyclotron-irradiated $^{86}$Sr for positron emission tomography (PET) imaging of the targeted organs [13]. At the present time, analysis or production of ultrapure radiolanthanides and $^{90}$Y is carried out by ion exchange [14] or on extraction chromatography columns [15], by inorganic exchangers [16] or even by solvent–solvent extraction [17]. Usually, these techniques are not available in a nuclear medicine laboratory due to radioprotection limitations.

Here we present the use of the metal ion imprinting concept for the production of a polymer suitable for the extraction of $^{90}$Y from a $^{90}$Sr source in one step to produce $^{90}$Y in a chemical form suitable for direct use in radiolabeling, thus reducing manipulations and radiological hazards. Another potential use of the polymer for the extraction of Eu(iii) from large volume of water (1 l) for nuclear power plant (NPP) monitoring will also be presented.

## Experimental

### *Polymer synthesis*

The experimental procedure for the synthesis of L, its yttrium complex [Y(L)$_3$] and the resin R has already been reported [18].

### *Distribution coefficients (D)*

All experiments were performed using $^{85}$Sr (94028 ± 990 Bq/ml), $^{95}$Zr (148000 ± 376 Bq/ml) and $^{88}$Y (74000 ± 2200 Bq/ml) standard solutions. The $^{85}$Sr and $^{88}$Y activities were determined *via* liquid scintillation

counting (LSC, Packard MINAXI TriCarb or LKB Wallac 1220) or by gamma-spectrometry (HPGe-detectors). $^{95}$Zr was determined by gamma-spectrometry. In order to determine the D values of the materials, 10 mg of the R resin were brought into contact with 0.9 ml of the respective solution in a 2 ml Eppendorf-Cap for 15 min. After the preconditioning 0.1 ml of a $^{85}$Sr or $^{88}$Y standard solution was added and the sample was shaken for 60 min. The solid phase was separated *via* centrifugation. Eventually a 0.5 ml aliquot of the solution was withdrawn. The determination of the activity of the withdrawn aliquots were performed relative to the standard solution used, the D values were calculated by using Eqn. (1):

$$D = \frac{\left[A_i - A_f\right]}{A_f} \cdot \frac{V}{m} \qquad (1)$$

where $A_i$ and $A_f$ are the initial and final activities, V is the volume of the solution and m the mass of the resin.

### *Europium Elution Profile*

2 mg of stable europium is added to 20 ml of water and the pH of the solution is adjusted between 3.5 and 4.5. This solution is passed through two cartridges (Supelco n° 57608-U) containing 0.3 g of resin R each. The cartridge was washed with 20 ml of distilled water at pH 3 then europium was eluted using 40 ml of HCl 0.1 M. During the process, 3 ml fractions were collected. Europium was determined by atomic emission (Perkin Elmer 4100, 454.5 nm) on each fraction to yield the elution profile.

### *Europium Extraction*

5 mg of stable europium is added to one liter of tap water (15°F) and the pH of the solution is adjusted between 3.5 and 4.5. This solution is pumped by a peristaltic pump through a chromatographic column (3 ml Supelco™ n° 57242 column) containing 1 g of the resin R at a rate of 2–5 ml/min. The column is washed with 10 ml of distilled water at pH 3 then europium is eluted with 15 ml of HCl (0.1 M). The elution solution is evaporated to dryness and the residue re-dissolved in a suitable quantity of HCl (0.1 M) for gamma-emission detection of $^{152}$Eu in a HPGe well detector. The yield of the chemical separation is determined on an aliquot of the solution by atomic emission.

## Results and Discussion

The novelty of the procedure used in this work concerns the type of complex involved in co-polymerization. In the literature examples of metal ion imprinting usually involve 1:1 or 1:2 ML$_n$ complexes.

Thus the versatility of the polymer extraction capacity and selectivity depends mainly on the cross-linking of the imprinted polymer: the larger the cross-linking, the larger the extraction capacity but the lower the selectivity. Murray and Southard [6] attribute these properties to the increased capacity of the polymer to adapt the coordination sites to different metal ions when the cross-linking is high. On the other hand, this leads to weaker selectivity. Meanwhile higher extraction capacity is observed due to the availability of more coordination sites. Thus adequate cross-linking is the key parameter to extraction capacity and selectivity. In this work, we chose a ML$_3$ imprinted complex with high cross-linking. The aim is to obtain a polymer with high extraction capacity due to high cross-linking and high selectivity due to the rigidity of the coordination cavity imposed by the three L ligands wrapped around the Y$^{3+}$ cation (Fig. 1). Metal ion selective molecularly imprinted polymer R was obtained by co-polymerization of the complex [Y(L)$_3$] with a mixture of styrene and divinylbenzene. L was obtained by derivation of dipicolinic acid in a two-step synthesis (Scheme 1). Synthesis and characterization of L, [Y(L)$_3$] and R will be published elsewhere [18]. After R is obtained, the crude polymer is coarsely ground in a mortar, washed successively in methanol, ethanol, and water:ethanol (90:10) several times. Finally, the product is washed with HCl (5 M) to remove the yttrium template, then several times with water and left to dry. After a final grinding, the polymer is sieved at 60–120, 120–170 and >170 mesh. It was recognized by different authors that strong washing with acid was necessary to remove as much imprinted cations as possible to increase the extraction capacity of the resin. Lemaire and co-workers [7] reported that unfortunately these washing steps with acid were responsible of the cleavage of ester into a carboxylic group when ethylene glycol dimethacrylate (EGDMA) was used instead of divinylbenzene (DVB) to obtain a more hydrophilic polymer. Thus we used the classical method of co-polymerization with styrene and DVB to obtain a robust polymer, even if the hydophobicity of this one renders its use in water somewhat problematic. Nevertheless this problem could be overcome by washing the polymer with ethanol:water 10:90 before use.

D values determined by using radioactive solutions are presented in Fig. 2. Large uncertainties are related to the difficulties of manipulating low quantities of the very hydrophobic polymer R, which in some cases prevents total contact of the polymer with the bulk solution containing the radionuclide. $^{88}$Y has a very high D value at pH above 2 while D values are very low regardless of the pH value for $^{85}$Sr. Moreover the size of the polymer particles plays a role in
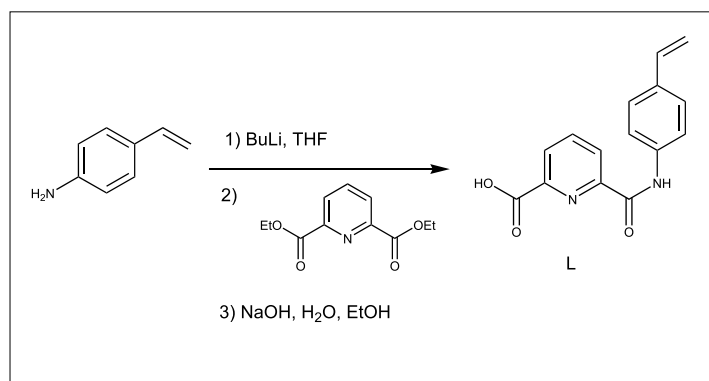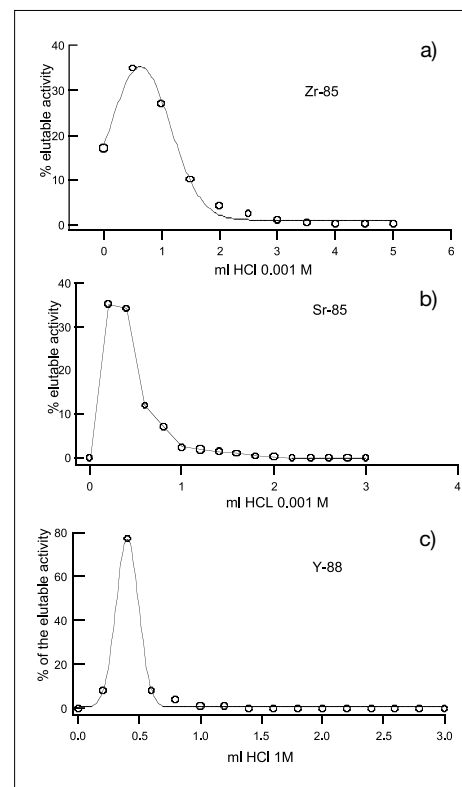
Scheme 1.
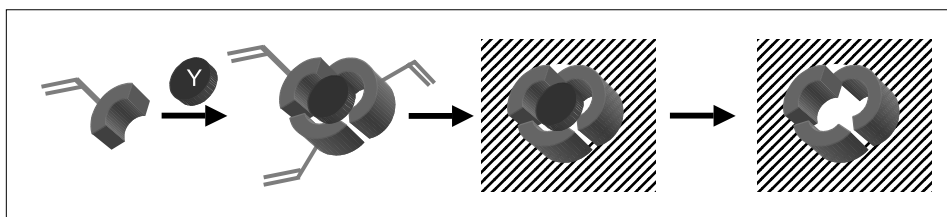


Fig. 1. Ionic imprinting of the [YL$_3$] complex in a polystyrene matrix, followed by the removal of the Y$^{3+}$ cation under acidic conditions
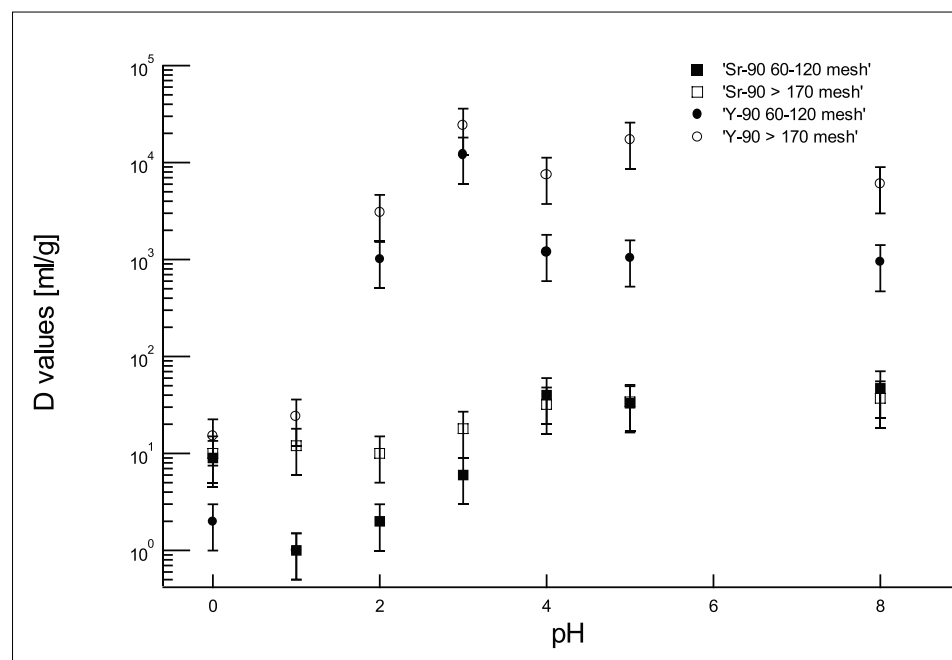


Fig. 2. Distribution coefficients (D) of $^{85}$Sr and $^{88}$Y as a function of the pH for two particle sizes (60–120 and >170 mesh) of the resin R



Fig. 3. Elution profile of $^{95}$Zr (a), $^{85}$Sr (b) and $^{88}$Y (c) when passed through a 200 mg column of resin R (>170 mesh) in a Fa.EiChrom® column

the $^{88}$Y D values for which higher values are measured for smaller particles size, *e.g.* > 170 mesh, while it does not play any role for $^{85}$Sr. Kimaro *et al.* [3] reported on the particle size effect on the extraction capacity and revealed same trends. Thus starting from a pH value of 3 very high decontamination factors from $^{90}$Sr can be expected by using 170 mesh R resin. Molecular imprinted resin based on dipicolinic acid allow extraction of yttrium at a relatively low pH due to the acidic characteristic of lanthanides and lanthanoïdes cations such as yttrium. Replacement of H$^+$ by Y$^{3+}$ can

then take place already at pH 2 where 50% of the extraction capacity of the resin (9 mg/g) is observed. Elution of such cations can be carried out by decreasing the pH, allowing re-protonation of the carboxylic groups of the resin. Total separation of $^{90}$Zr (stable daughter product of $^{90}$Y) is also required to increase the yield of radiolabelling. An experiment with a mixture of $^{85}$Sr, $^{95}$Zr and $^{88}$Y shows that Sr and Zr are not extracted and that 100% of the extractable activity of $^{88}$Y fixed on 200 mg of resin R can be eluted with less than one ml of HCl (1 M) (Fig. 3). Such diluted media are of

interest for radio-labelled medical applications.

In another experiment, the elution profile of europium cation shows that it is possible to extract europium from water and to remove europium from the column by using diluted acid such as HCl (0.1 M) in a small volume (Fig. 4). Experiments carried out on 1 l of tap water (15°F) show an extraction yield of over 75%.

## Conclusions

The metal ion imprinted concept has been used to obtain a polymer with satisfactory extraction capacity and selectivity for environmental analysis of $^{152}$Eu in water and production of $^{90}$Y for potential medical use. In the case of environmental analysis of $^{152}$Eu the requirement is to extract lanthanides from a matrix containing essentially alkaline and alkaline-earth cations. In this case selectivity based on dipicolinic acid–cation interactions and on the rigidity of the complexation cavity induced by co-polymerization of [Y(L)$_3$] is satisfactory to extract micro-quantities of lanthanide and lanthanoïde cations from macro-quantities of alkaline and alkaline-earth cations. Production of medical grade $^{90}$Y from a $^{90}$Sr source should be possible with R due to the large difference in D values for these two cations at pH 3. Moreover the elution of $^{90}$Y
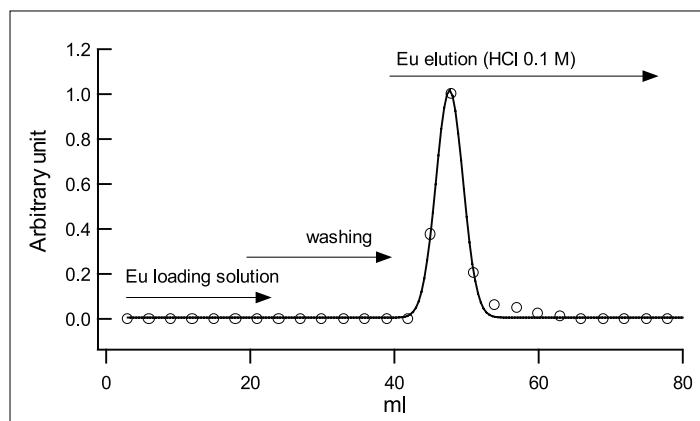
Fig. 4. Chromatography profile of Eu$^{3+}$ (2 mg) on a column of 0.6 g of R

in a small quantity of diluted hydrochloric acid allows for direct use in radiolabelling.

Thus metal ion imprinted materials, though not yet in use in radiochemical separation to our knowledge, could be of great help for the analysis of radionuclides in environmental samples, as well as for the production of medical grade radionuclides: the low extraction capacity of such material regarding classical cationic or anionic exchanger (*e.g.* Dowex or AG resins) is overcome by the high specific activity of radioactive material resulting in very few atoms being involved in the extraction process. In this respect, only selectivity has to be tuned to improve separation.

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