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Syntheses and Characterization of Gold(III) Tetradentate Schiff Base Complexes. X-ray Crystal Structures of [Au(sal$_2$pn)]Cl·2.5H$_2$O and [Au(sal$_2$en)]PF$_6$

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A number of gold(III) complexes containing tetradentate Schiff base ligands have been synthesized and characterized. Gold(III) forms four-coordinate square planar complexes with these ligands. These complexes have been characterized by their elemental analyses and UV−visible, infrared, NMR, and mass spectra. Preliminary radiochemical studies with Au-198 show that these complexes are also formed at the tracer level from (Bu$_4$N)-[^{198}AuCl$_4$]. [Au(sal$_2$pn)]Cl (sal$_2$pn = *N*,*N*′-propylenebis(salicylideneimine)), AuC$_{17}$H$_{16}$N$_2$O$_2$Cl·2.5H$_2$O, cystallizes from acetonitrile in the triclinic space group $P\bar{1}$ with $a = 6.6646(8)$ Å, $b = 10.2788(13)$ Å, $c = 14.2128(18)$ Å, $\alpha = 70.415(2)°$, $\beta = 77.705(2)°$, $\gamma = 86.777(2)°$, $Z = 2$, $R = 0.0286$, and $R_w = 0.0722$. [Au(sal$_2$en)]PF$_6$ (sal$_2$en = *N*,*N*′-ethylenebis(salicylideneimine)), AuC$_{16}$H$_{14}$N$_2$O$_2$PF$_6$, crystallizes from ethanol in the triclinic space group $P\bar{1}$ with $a = 7.2730(9)$ Å, $b = 10.9930(14)$ Å, $c = 12.1882(16)$ Å, $\alpha = 112.472(2)°$, $\beta = 93.631(2)°$, $\gamma = 98.251(2)°$, $Z = 2$, $R = 0.0365$, and $R_w = 0.0995$.

Introduction

Gold-199 is a reactor-produced radionuclide considered as one of the potential radioisotopes for use in therapeutic nuclear medicine.[1−3] Gold-199 is a beta particle (β^-) emitter ($E_{\max} = 0.46$ MeV) with a half-life of 3.15 days. It also emits γ photons ($E_\gamma = 158$, 208 keV), which are suitable for external detection by the single-photon imaging instrumentation used in nuclear medicine departments for diagnostic imaging. This would allow the localization of the radiotherapeutic drug to be followed. More importantly, ^{199}Au is available in high specific activity (i.e., virtually all of the Au atoms present are ^{199}Au). The high specific activity would make it amenable for targeting limited numbers of receptors on tumor cells. For use in radiotherapy, a complex of gold must be kinetically stable to substitution and reduction under biological conditions, namely, 37 °C and pH 7.4 blood. The low-spin d^8 configuration of Au(III) is considered kinetically inert compared to d^{10} Au(I), and we are investigating the chemistry of Au(III) with nitrogen- and oxygen-containing tetradentate ligands.

Although Au-199 has suitable nuclear properties, it has not been extensively pursued for radiotherapy applications perhaps for some of the same reasons Au(III) coordination chemistry is relatively scarce in the literature. Gold(III) is difficult to work with because it is unstable to reduction; it readily undergoes hydrolysis reactions, and Au(III) complexes often precipitate as AuCl$_4^-$, AuCl$_2^-$, or mixed AuCl$_4^-$/AuCl$_2^-$ salts that exhibit limited solubility and prove to be difficult to characterize. Reports of gold(III) complexes in the literature show them to be predominantly square planar in geometry, with a variety of ligands coordinated to the metal center. Amine,[4−11] imine,[12−16] Schiff base,[17−20] amide,[21−23] and thiolate[24−26] ligands have all been reported to form gold(III) complexes.

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The chemistry of gold(III) with the classical tetradentate Schiff base ligands such as acac$_2$en and sal$_2$en has not been explored in any depth, although complexes with these ligands have been reported for most metals,[27,28] including Au(III). However, the Au(III) complexes were not well characterized (only elemental analyses and IR and ionophoric behavior have been reported).[17,20] To this end, we have developed a new method for synthesizing Au(III) complexes with tetradentate Schiff base ligands using (Bu$_4$N)[AuCl$_4$] as the starting material and have fully characterized the resultant complexes. The complexes reported are characterized by their elemental analyses and FT-IR, NMR, MS, and UV−vis spectra. [Au(sal$_2$pn)]Cl·2.5 H$_2$O and [Au(sal$_2$en)]PF$_6$ have been characterized by X-ray crystallography, which confirms their structural assignments. In addition, preliminary radiotracer ^{198}Au chemistry with the Schiff base ligands is reported. The radiotracer studies used ^{198}Au rather than the high specific activity ^{199}Au because of its easier production and cost for the preliminary radiochemistry development. The production of ^{198}Au involves irradiation of a natural Au target (100% ^{197}Au), while the production of ^{199}Au involves irradiation of a very expensive enriched ^{198}Pt target (^{198}Pt is 7.2% of natural Pt) and an involved subsequent separation of the ^{199}Au produced from the Pt target. Although ^{198}Au has nuclear properties ($t_{1/2} = 2.7$ d, $E_{\max}(\beta^-) = 0.96$ MeV, $E_\gamma = 412$ keV) very similar to those of ^{199}Au, the presence of nonradioactive carrier ^{197}Au would limit its applicability for radiotherapy; less than 1% of the total Au atoms become radioactive during a typical production run from ^{197}Au.

Experimental Section

General. Gold metal and NaAuCl$_4$ were purchased from Aesar Chemical Company. Salicylaldehyde, acetylacetone, ethylenediamine, 1,3-propanediamine, tetrabutylammonium chloride, and ammonium hexafluorophosphate were purchased from Sigma-Aldrich Chemical Co. All reagents were used without further purification. Silica gel IB−F (Bakerflex) TLC plates, cellulose (100 μm) TLC plates, and microcrystalline cellulose (20 μm) were purchased from Sigma-Aldrich Chemical Co. All solvents and acids used were reagent grade, purchased from Fisher Scientific, and used without further purification. Only distilled, deionized water was used. ^{198}Au was prepared at the Missouri University Research Reactor (MURR) by the (n,γ) reaction on natural gold wire. A 1.0 mg sample of Au wire was irradiated in a pneumatic tube position in the reactor at a thermal neutron flux of 4×10^{13} n cm^{-2} s^{-1}. Plexiglas and lead shielding were used when working with ^{198}Au, and proper radiation safety procedures were followed at all times by trained personnel in radiation-approved laboratories.

Physical Measurements. UV−visible spectra were recorded on a Hewlett-Packard 8452A diode-array spectrophotometer. Infrared spectra were obtained as KBr pellets and recorded on a Nicolet 20DXB FT-IR spectrometer. ^{1}H NMR and ^{13}C NMR spectra were obtained in CDCl$_3$, d$_6$-DMSO or d$_3$-CD$_3$CN on a Bruker ARX-250 or AMX-500 spectrometer. TMS was used as an internal reference for the ^{1}H NMR spectra. Elemental analyses were performed by Oneida Research Services in Whitesboro, NY. Matrix-assisted laser desorption ionization (MALDI) mass spectra were obtained in a 2,5-dihydroxybenzoic acid matrix using a time-of-flight mass spectrometer in the linear mode.

A Bioscan 200 TLC scanner was used to obtain radioactivity traces of thin-layer chromatography (TLC) plates, paper chromatographs, and electrophoresis strips obtained from ^{198}Au experiments. The detection system utilizes a gas ionization detector (ca. 100% efficient for β^- radiation, ca. 2% efficient for γ radiation). NaI(Tl) well counters were used for assaying liquid samples containing ^{198}Au.

HAuCl$_4$. Tetrachloroauric acid was prepared by dissolving gold metal in aqua regia, evaporating the acid with heat, adding HCl and reducing the volume several times, and then adding water and reducing the volume several times to remove the excess acid. The final product was obtained as a hygroscopic yellow-orange solid, which gave a pH of ca. 1 in solution.

(Bu$_4$N)AuCl$_4$. Tetrabutylammonium tetrachloroaurate was prepared from the acid, HAuCl$_4$, in dilute HCl (0.01 M) by the addition of tetrabutylammonium chloride. The desired product precipitated as a yellow-orange solid almost immediately. It was collected by filtration, washed with diethyl ether, and vacuum-dried.

Schiff Base Ligands. The Schiff base ligands used in this study, H$_2$sal$_2$en, H$_2$sal$_2$pn, H$_2$acac$_2$en, and H$_2$acac$_2$pn, were prepared using a literature method.[29,30] Briefly, 2 equiv of the salicylaldehyde were condensed with 1 equiv of the diamine in refluxing ethanol. Cooling yielded the crude product. The product was collected by filtration, washed with cold ethanol, and air-dried. The product was recrystallized from hot ethanol. The melting points and NMR spectra (^{1}H and ^{13}C) were consistent with literature reports.

1. [Au(sal$_2$pn)]AuCl$_4$. A solution of 0.50 g (1.26 mmol) of NaAuCl$_4$·2H$_2$O in 40 mL of absolute EtOH was slowly added to a stirring solution of 0.712 g (2.52 mmol) of H$_2$sal$_2$pn dissolved in 42 mL of CH$_2$Cl$_2$/17 mL EtOH (abs). The mixture was stirred at room temperature for 5 min and was then heated at 40 °C for 30 min during which time the mixture progressed from yellow to dark amber in color, and a dark red-brown precipitate formed. After it was cooled in the freezer overnight, the solid was collected by filtration, washed with CH$_2$Cl$_2$, and dried under vacuum. Yield: 0.78 g (76% based on Au). ^{1}H NMR (d$_6$-DMSO): 2.346 ppm (m, 2H, CH$_2$CH_2CH$_2$), 4.145 ppm (m, 4H, NCH_2), 6.933−7.691 ppm (mm, 8H, phenyl), 8.596 ppm (s, 2H, N=CH).

2. [Au(sal$_2$pn)]Cl·2.5H$_2$O. To a stirring solution of (Bu$_4$N)AuCl$_4$ (0.0130 g, 0.0373 mmol) in 1 mL of CH$_2$Cl$_2$ was added NH$_4$PF$_6$ (0.0326 g, 0.20 mmol) in 1 mL of EtOH. H$_2$sal$_2$pn (0.0424 g, 0.15 mmol) in 1 mL of CH$_2$Cl$_2$ was then added dropwise. The reaction mixture was heated at 40 °C for 20 min and then cooled to room temperature. The orange-brown reaction mixture was capped and put in the freezer (−20 °C) overnight, during which time the product precipitated as an orange-brown solid. The product was collected by filtration, washed with diethyl ether (2×5 mL), and dried in vacuo. Yield: 0.0132 g (53%). Recrystallization from acetonitrile yielded X-ray-quality crystals. MALDI mass spectrum: M$^+$ at 476.805 (477.088 calcd). ^{1}H NMR (CD$_3$CN): 2.38 ppm (m, 2H, CH$_2$CH_2CH$_2$), 4.10 ppm (m, 4H, NCH_2), 6.95−7.67 ppm (mm, 8H, phenyl), 8.14 ppm (s, 2H, N=CH). ^{13}C NMR (CD$_3$CN): 28.254 ppm, (CH$_2$$CH_2CH_2$), 59.058 ppm (N$CH_2$), 117.658, 119.137, 136.211, 140.498 ppm (aromatic), 161.168 ppm (phenolic), 164.672 ppm (N=CH). UV−visible spectrum (CH$_3$CN; λ (ϵ)): 370 nm (8920), 272 nm (56 800), 236 nm (sh, 61 000). FT-IR (KBr pellet): 1550−1650 cm^{-1} (C=N, aromatic).

3. [Au(sal$_2$en)]AuCl$_4$. This compound was prepared as described above for [Au(sal$_2$pn)]AuCl$_4$, substituting the equivalent molar quantity of H$_2$sal$_2$en for H$_2$sal$_2$pn. Yield: 0.445 g (44% based on Au). ^{1}H NMR (d$_6$-DMSO): 4.204 ppm (s, 4H, NCH_2), 6.993−7.781 ppm (mm, 8H, phenyl), 8.939 ppm (s, 2H, N=CH).

4. [Au(sal$_2$en)]PF$_6$. This compound was prepared as described above for [Au(sal$_2$pn)]Cl, substituting the equivalent molar quantity of H$_2$sal$_2$en for H$_2$sal$_2$pn. X-ray-quality crystals were obtained from ethanol at room temperature. Yield = 0.0183 g (83%). Anal. Calcd for AuC$_{16}$H$_{14}$N$_2$O$_2$PF$_6$ (found): C, 31.60 (31.90); H, 2.32 (2.84); N, 4.60 (4.62). MALDI mass spectrum: M$^+$ at 462.988 (463.072 calcd). ^{1}H NMR (CD$_3$CN): 4.179 ppm (s, 4H, NCH_2), 7.002−7.775 ppm (m, 8H, aromatic), 8.495 ppm (s, 2H, N=CH). ^{13}C NMR (CD$_3$CN): 62.33 ppm (NCH$_2$), 119.38, 120.18, 120.92, 136.85, 140.62 ppm (aromatic), 161.63

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(phenolic), 162.66 (N═CH). UV−visible spectrum (CH_3CN; λ (ϵ)): 374 nm (3870), 268 nm (22 700), 242 nm (23 400). FT-IR (KBr pellet): 1637, 1604 cm^{-1} (C═N, aromatic), 841 cm^{-1} (PF_6^-).

Radiochemistry. The radiochemical studies involved the use of ^{198}Au, which was produced at the Missouri University Research Reactor (MURR) through an (n,γ) reaction.

$$^{197}\mathrm{Au} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{198}\mathrm{Au} + \gamma \xrightarrow{2.694\ \mathrm{d}} {}^{198}\mathrm{Hg(stable)} + \beta^-$$

The Au wire irradiated in this manner contains both ^{197}Au and ^{198}Au, with most of the gold being ^{197}Au.

1. $H^{198}AuCl_4$. The irradiated gold target (1 mg Au wire, 7.7 mCi ^{198}Au) was dissolved in 0.300 mL of aqua regia with heating (boiling water bath). The solution was taken close to dryness, 0.300 mL of concentrated HCl was added, and the resulting solution was again taken close to dryness. This step was repeated twice. Distilled, deionized water (0.300 mL) was added, and the resulting solution was again evaporated to near dryness. This step was repeated, and the residue was dissolved in 0.500 mL of H_2O to yield the $H^{198}AuCl_4$ stock solution.

2. $(Bu_4N)^{198}AuCl_4$. Tetrabutylammonium chloride (1.00 mL, 0.1 M) was added to the $H^{198}AuCl_4$ stock solution (3.3 mCi), and the resulting $(Bu_4N)^{198}AuCl_4$ was extracted into $CHCl_3$ (2 × 1.00 mL) with close to 100% efficiency to give a stock solution containing 3.15 mCi/1.9 mL.

3. $[^{198}Au(sal_2pn)]^+$. The radiochemical studies involved using $(Bu_4N)^{198}AuCl_4$ as the starting compound for complexation. To 10 μL of $(Bu_4N)^{198}AuCl_4$ in $CHCl_3$ containing 50 μCi (2 MBq) was added $(Bu_4N)AuCl_4$ (0, 15, or 30 μL, 0.032 M) in CH_2Cl_2, H_2sal_2pn (10−160 μL, 0.1 M) in CH_2Cl_2, NH_4PF_6 (20−320 μL, 0.1 M) in EtOH (abs), and CH_2Cl_2 (to give 1.00 mL total volume). The resultant reaction mixture was heated to 40 °C in a water bath. The effects of [$AuCl_4^-$] (millimolar to micromolar), [H_2sal_2pn], [NH_4PF_6], temperature, and time on the complexation yield of [$^{198}Au(sal_2pn)^+$] were determined. The optimal conditions for the syntheses of the complexes were determined to occur at a ligand-to-metal ratio of 5:1. The radiochemical reactions were analyzed by paper electrophoresis (0.05 M phosphate buffer (pH 6.5), 300 V, 3 h) and TLC on cellulose plates. By use of cellulose TLC plates, the desired complex had an $R_f = 0$ with $CHCl_3$ as the eluent, while the uncomplexed ligand and Bu_4NAuCl_4 migrated with $R_f = 1$ (with the solvent front). All three species moved with the solvent front when acetonitrile was the eluent. Colloidal gold remained at the origin under all solvent conditions. These same TLC methods are applicable to the characterization of the nonradioactive gold reactions, with a 1% hydrazine solution being used to visualize the gold-containing species.

X-ray Crystal Structure Analyses. Intensity data were obtained at −100 °C on a Bruker SMART CCD area detector system using the ω scan technique with Mo Kα radiation from a graphite monochromator. Intensities were corrected for Lorentz and polarization effects. Equivalent reflections were merged, and absorption corrections were made using the multiscan method. Space group, lattice parameters, and other relevant information are given in Table 1. The structure was solved by direct methods with full-matrix least-squares refinement, using the SHELX package.[31,32] All non-hydrogen atoms were refined with anisotropic thermal parameters. The hydrogen atoms, except those of the waters of crystallization, were placed at calculated positions and included in the refinement using a riding model, with fixed isotropic *U*. The final difference map contained no features of chemical significance.

Results and Discussion

The gold(III) Schiff base complexes were prepared by direct substitution onto tetrachloroaurate. The acid form, the sodium salt, and the tetrabutylammonium salt of tetrachloroaurate all yield the desired product, although the syntheses are much more efficient from $(Bu_4N)AuCl_4$. The latter eliminates the acidic environment of the $HAuCl_4$ reactions that can interfere with complexation. In addition, it avoids the formation of the problematic tetrachloroaurate product salts. The Au(III) complexes of the form [Au(Schiff base)]X were prepared and fully characterized for the Schiff base ligands H_2sal_2en and H_2sal_2pn. Elemental analyses of the resultant complexes were consistent with the proposed formulations. Attempts to prepare the analogous complexes with the acetylacetone-derived Schiff base ligands resulted only in the rapid formation of colloidal gold.

Table 1. Crystallographic Data Collection Parameters for $[Au(sal_2en)]PF_6$ and $[Au(sal_2pn)]Cl{\cdot}2.5H_2O$

	$[Au(sal_2en)]PF_6$	$[Au(sal_2pn)]Cl{\cdot}2.5H_2O$
formula	$AuC_{16}H_{14}N_2O_2PF_6$	$AuC_{17}H_{16}N_2O_2Cl{\cdot}2.5H_2O$
fw	608.23	557.77
space group	$P\bar{1}$	$P\bar{1}$
a, Å	7.2730(9)	6.6646 (8)
b, Å	10.9930(14)	10.2788(13)
c, Å	12.1882(16)	14.2128(18)
α, deg	112.472(2)	70.415(2)
β, deg	93.631(2)	77.705(2)
γ, deg	98.251(2)	86.777(2)
V, Å^3	883.7(2)	896.15(19)
Z	2	2
ρ_{calc}, g/cm^3	2.286	2.067
temp, K	173(2)	173(2)
μ, cm^{-1}	84.9	83.86
λ source, Å	0.710 70	0.710 73
$R(F)$ [a]	0.0365	0.0286
$R_w(F)$ [b]	0.0995	0.0722
GoF	0.902	1.043

[a] $R = \sum||F_o| - |F_c||/\sum|F_o||$. [b] $R_w = [\sum\bar{w}(|F_o^2| - |F_c^2|)^2/\sum\bar{w}(|F_o^2|)^2]^{1/2}$.

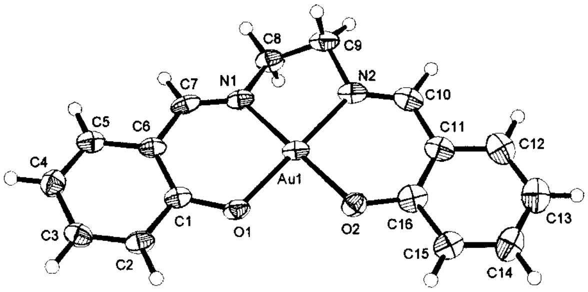

Figure 1. ORTEP (50% probability ellipsoids) representation of $[Au(sal_2en)]^+$.

Characterization of [Au(sal$_2$en/pn)]X (X = $AuCl_4^-$, Cl^-, or PF_6^-). The Au(III) complexes were characterized by their UV−visible, FT-IR, ^{1}H NMR, ^{13}C NMR, and MALDI mass spectra. The UV−visible spectra of these Au(III) complexes show absorbances at about 370, 270, and 240 nm. The FT-IR spectra show the expected C═N and aromatic stretches at ca. 1550−1650 cm^{-1} and a strong absorbance for the PF_6^- anion at ca. 840 cm^{-1}. The NMR spectra (^{1}H and ^{13}C NMR) are consistent with coordination of the Schiff base ligand with Au(III). The spectra indicate the complexes are symmetrical, consistent with the square planar coordination geometry observed with Au(III) complexes. Most of the proton and carbon resonances are observed downfield relative to the free ligand. MALDI mass spectra of the two complexes in a 2,5-dihydroxybenzoic acid matrix showed the presence of the molecular ion of the cation.

X-ray Crystal Structure Analyses. Both $[Au(sal_2en)]PF_6$ and $[Au(sal_2pn)]Cl{\cdot}2.5\ H_2O$ were analyzed by X-ray diffraction analysis, with the ORTEP representations (with 50% probability ellipsoids shown) of the two structures shown in Figures 1 and 2, respectively. Both structures showed the Au(III) to be in the

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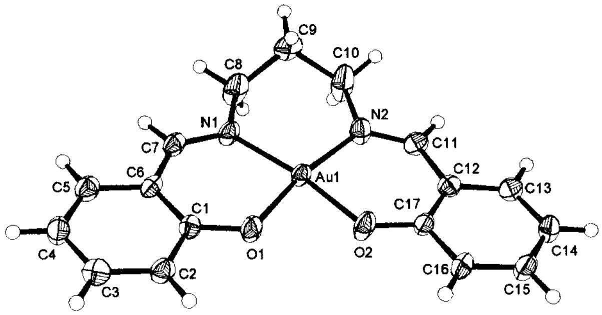

Figure 2. ORTEP (50% probability ellipsoids) representation of $[Au(sal_2pn)]^+$.

Table 2. Selected Bond Distances (Å) and Bond Angles (deg) for $[Au(sal_2en)]PF_6$ and $[Au(sal_2pn)]Cl{\cdot}2.5H_2O$

	$[Au(sal_2en)]PF_6$	$[Au(sal_2pn)]Cl{\cdot}2.5H_2O$
Au−O1	1.963(4)	1.980(4)
Au−O2	1.977(4)	1.978(3)
Au−N1	1.977(5)	2.009(4)
Au−N2	1.962(5)	2.017(4)
O1−Au−N1	95.0(2)	92.83(16)
N1−Au−N2	84.0(2)	97.12(18)
N2−Au−O2	95.9(2)	92.73(16)
O2−Au−O1	85.0(2)	77.32(15)
N2−Au−O1	178.7(2)	170.04(15)
N1−Au−O2	178.5(2)	170.15(15)

center of a square plane, coordinated to two imine nitrogen atoms and two phenolic oxygen atoms. Table 2 gives selective bond distances and bond angles for the two structures. The Au−N distances observed range from 1.962 to 2.032 Å, while the Au−O distances range from 1.963 to 1.995 Å. These distances are consistent with Au−N and Au−O bond distances reported in the literature (Au−N, 1.928−2.216 Å; Au−O, 1.985−2.02 Å).[7−9,11,14,15,20−23,26] The biggest difference between the two structures lies in the angles about the central Au(III) atom, which is a result of the bite angle constraints imposed by the en vs pn backbone between the two imine nitrogens. The five-membered chelate ring (en backbone) had an angle of ca. 84° about the Au(III), while the six-membered pn backbone had an angle of ca. 97°. The six-member chelate rings from the salicylaldimine portion of the molecules have angles of 92−96° about the Au(III). These angles are consistent with literature reports for five- and six-membered chelate rings with Au(III).[7−9,11,15,20−23,26] The open O−Au−O angle in both structures is 360° minus the sum of the other three angles about the Au(III). The Au(III) atom essentially sits in the plane defined by the four coordinating atoms of the ligand, being 0.0043 Å above the least-squares plane defined by the four coordinating atoms of the sal_2pn ligand and 0.0211 Å above the least-squares plane defined by the four coordinating atoms of the sal_2en ligand. The Au(III) appears to be sterically constrained within the $[Au(sal_2en)]^+$ structure; the two ethylene carbons (C8 and C9) are only 0.224 Å above and 0.4078 Å below the plane defined by the sal_2en ligand. The ethylene backbone is constrained by the sp^2 imine nitrogens and by the size of Au(III), and the strain imposed by the en group is taken up by the open O−Au−O angle. The central methylene group in the propylene backbone of $[Au(sal_2pn)]^+$ exhibits a positional disorder with about 50% occupancy at each site.

Radiochemistry Studies. Radiochemistry studies (i.e., spiked with ^{198}Au) allowed us to determine that when $HAuCl_4$ or $NaAuCl_4$ was the starting material, the maximum yield of the reaction was 50% $[Au(sal_2en/pn)^+]$ because of precipitation of the insoluble $AuCl_4^-$ salt. We found that 50% of the Au was present as $[Au(sal_2en/pn)^+]$ and 50% as $AuCl_4^-$, using TLC and electrophoresis. The cationic $[Au(sal_2en/pn)^+]$ migrated toward the cathode, while the tetrachloroaurate anion migrated toward the anode. When the reactions were run without the addition of macroscopic amounts of tetrachloroaurate, the $[Au(sal_2en/pn)^+]$ species was not formed. This appears to be due to the high acidity (pH ca. 1−2) of $H^{198}AuCl_4$ prepared from the irradiated gold wire. Attempts to increase the pH in the absence of macroscopic amounts of tetrachloroaurate resulted only in the formation of colloidal Au(0). This led us to develop a synthetic method for these Au(III) Schiff base complexes where $(Bu_4N)AuCl_4$ was the starting material. The tetrabutylammonium salt of tetrachloroaurate is readily extracted into chloroform and thus could be easily separated from the high acid solution of the dissolved irradiated Au wire.

The synthesis of the Au(III) Schiff base complexes from $(Bu_4N)AuCl_4$ requires the presence of NH_4PF_6 and ethanol to proceed, in addition to the Schiff base ligand. The absence of either of these reagents prevents the desired product formation. The PF_6^- anion appears to be necessary to break up the $(Bu_4N)AuCl_4$ ion pair, and the ethanol must facilitate this. Carrying out the reaction in 100% chloroform gives no product, as does running the reaction in a chloroform/ethanol mix but without PF_6^-. In addition, the $(Bu_4N)AuCl_4$ ion pair must be sufficiently stable in the reaction medium (CH_2Cl_2/EtOH) to prevent the precipitation of $[Au(Schiff\ base)]AuCl_4$. The Schiff base ligand itself acts as the proton scavenger in these reactions, and a ligand to metal ratio of 5:1 was found to give the highest yield of product. Attempts to use triethylamine or hindered bases such as 2,6-lutidene complicated the purification of the products and resulted in colloidal gold formation. Reactions using $(Bu_4N)^{198}AuCl_4$ resulted in product, even in the absence of added macroscopic quantities of $(Bu_4N)AuCl_4$. The yields observed for the radiochemical tracer studies ranged up to 95−100%, which is higher than the isolated yields reported for the macroscopic syntheses. At radiotracer concentrations, reactions are often different from those at macroscopic levels.

Conclusions

Although the Au(III) complexes with the tetradentate Schiff base ligands sal_2en and sal_2pn have been previously reported, no characterization other than elemental analyses, IR spectra, and ionic migration were reported.[17,20] The earliest report of these complexes was in 1965 when NMR was not readily available, and certainly not in the Fourier transform mode used today. We report the synthesis of $[Au(sal_2en/pn)]X$ with full characterization of the complexes. We have improved the syntheses of the complexes by developing a method based on $(Bu_4N)AuCl_4$ as the starting material. This new synthetic method for preparing $[Au(sal_2en/pn)]PF_6$ should be amenable to the preparation of gold(III) complexes with other ligands and may make this chemistry more accessible by eliminating the problems associated with the precipitation of insoluble tetrachlorate salts and the use of acidic conditions. The radiochemistry studies allowed us to optimize the reactions and show that these complexes can be prepared at the radiotracer level. The extension of this chemistry to the high specific activity ^{199}Au level (nM or lower concentrations) may be achievable using the procedures developed here.

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Supporting Information Available: Experimental details, listings of bond distances, bond angles, thermal parameters, torsion angles, and least-squares planes for [Au(sal$_2$pn)]Cl$\cdot$2.5H$_2$O and [Au(sal$_2$en)]PF$_6$. This material is available free of charge via the Internet at http://pubs.acs.org.

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