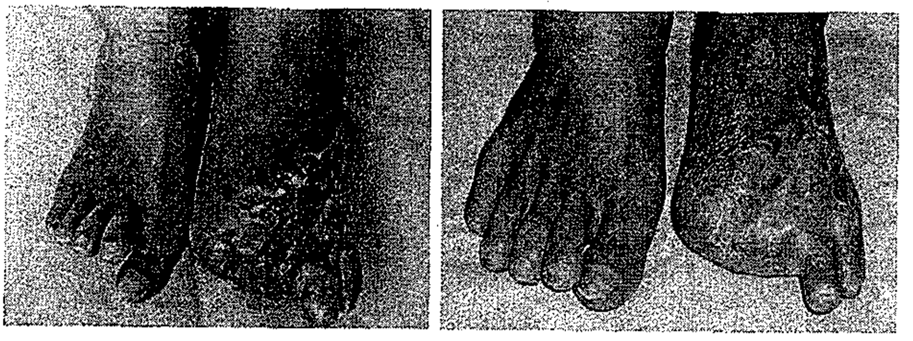

図 1．バージャー病の下肢皮膚潰瘍
移植治療前は左第 1 趾から第 3 趾まで広範な皮膚潰瘍を認めたが(左)，移植治療 3 ヵ月後には完全に上皮化された(右).

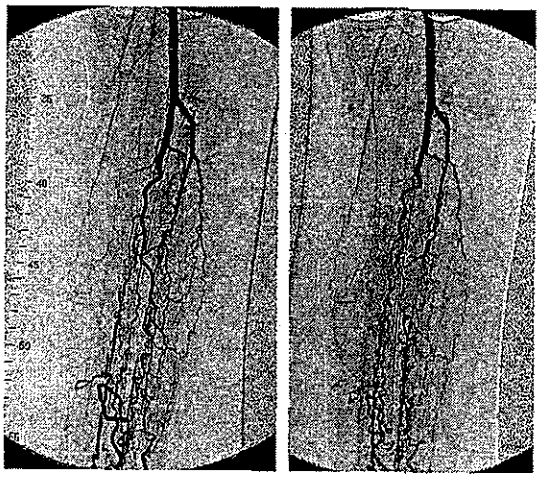

図 2．下肢血管造影
移植治療前の血管造影と比較し(左)，移植治療 1 ヵ月後に血管周辺にもやもや像は認めるが，新生血管の評価は困難である(右).

含めた臨床検査では臨床症状の改善を十分には反映しなかった(図 2)．一般に，治療効果の判定として血管造影法(DSA)が施行される．しかし，既存の血管造影装置の解像度は約 200〜300 μm であり，再生される新生血管は約 100 μm 程度の微小血管であり，その評価は困難である．症例によっては血管数の増加がみられることがあるが，側副血行路の発達(arteriogenesis)と考えられており，再生した血管そのものが造影されているわけではない．そこで，再生された新生血管が臨床症状の改善に関与していることを証明するには，再生血管を描出することが重要である．これら，再生された微小血管を血管造影検査で評価するためには，微量の造影剤を検出できる装置が必要となる．その要素としては X 線が高輝度で，平行化，単色化の性質を持ち，検出系を高感度，高解像度化することが重要である．

現在のところ，これらの要素をすべて取り揃えているのが放射光施設内の微小血管造影装置であり，微小血管の検出を可能としている[5]．放射光の詳細については他稿に委ねるが，簡単に列記する．放射光とは広域のスペクトルを持つ白色光であり，太陽光のように限りなく平行に近い性質がある．その白色光に対しシリコン結晶を用い，ヨード吸収端の直上に設定することにより単色化が可能となる．現在のところ，微小血管の描出を可能にしているのは放射光を用いた微小血管造影法だけである．しかし，放射光施設は多額のコストと広大な敷地を必要とし，臨床導入するには時間的・空間的にも問題がある．そこで微小血管造影法が臨床応用できるように，新エネルギー・産業技術開発機構(NEDO)の支援により，病院設置型の微小血管造影装置を浜松ホトニクス・NHK エンジニアリング

の協力を得て，共同開発した．

微小血管造影法に必要な要素

1．高輝度

輝度は単位面積あたりのX線のフォトン量であり，イメージングプレートに像を映し出す重要な要素である．X線は被写体を通過する時に散乱・吸収されるため，検出器に到達する前にそのフォトン量は顕著に減衰する．こうした理由で既存の血管造影装置は，X線のフォトン量を維持するために白色光で撮影している．放射光のX線は，既存のX線装置より約10^8倍も輝度が高く，被写体によりX線の減衰を受けても，十分なフォトン量を維持することが可能である．X線を単色化する行程で，著しくフォトン量を減少させたとしても，既存の白色X線と同等のフォトン量を検出器に確保することができる．この要素は，微小血管造影には必要不可欠である．

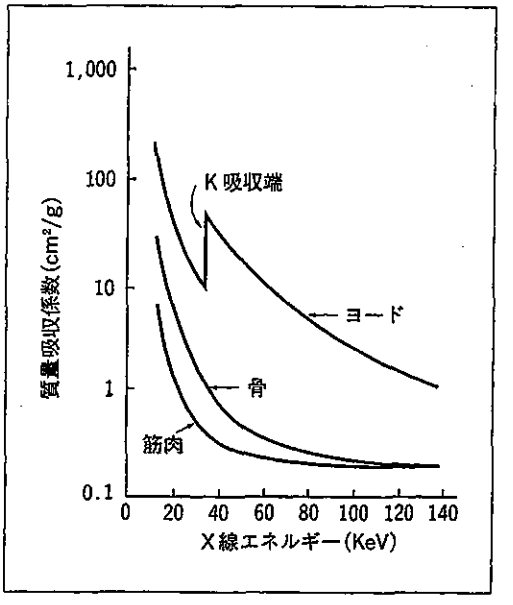

図3．X線エネルギーと質量吸収係数の関係
33.3keV直上でヨードK吸収端が上昇し，組織との質量吸収係数を最大にする．

2．単色化

ヨードは33.3 keVのエネルギーレベルでK吸収端を持つ．これは質量吸収係数が不連続に上昇し，X線のエネルギーをヨードのK吸収端の直上のエネルギーに変換すると，ヨードと周囲組織との質量吸収係数の差が最大となる．組織とヨードとのコントラストが最良となるため，微量のヨードを検出できやすくする効果がある(図3)．放射光をシリコン結晶によるBragg反射を応用し，その角度により必要な単色エネルギーを得ることができる(図4)．

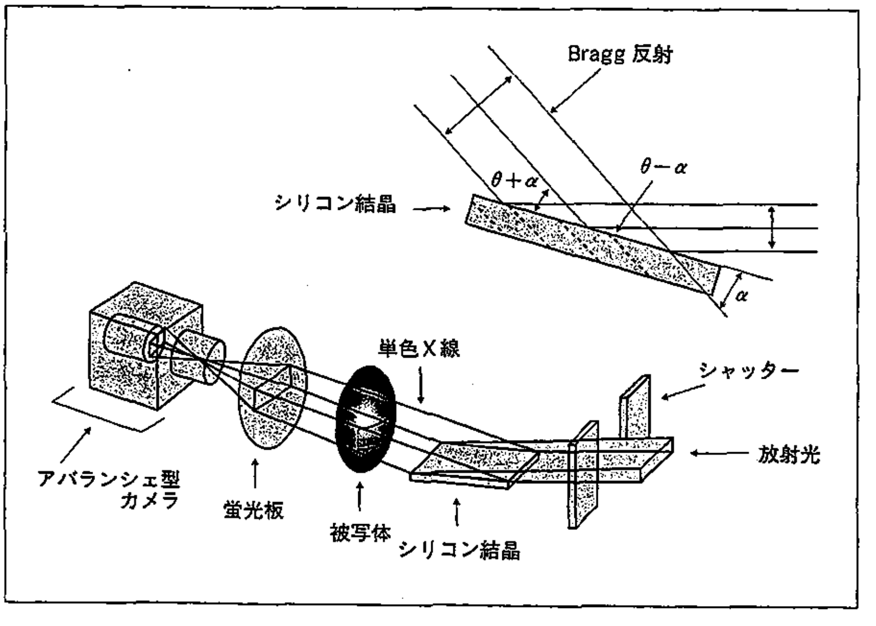

図4．放射光施設の微小血管造影システム
放射光をシリコンを用いBragg反射させ，その角度を調節し，単色X線を得る．その像は高感度，高解像度のアバランシェ型カメラで撮影される．

3．平行化

平行線により映し出された像は，理論的にいえば等大の大きさになる．非平行光線は被写体から像との距離が離れるほど像は拡大し，辺縁がぼやけてしまう(図5)．放射光のX線は限りなく平行な性質であり，これも微小血管造影に理想的である．一方，既存のX線は平行線ではなく，微小血管レベルの評価に影響するため，微小血管造影には不向きである．浜松ホトニクスが開発した微細な孔を多数有するキャピラリープレートを用いると，X線を平行化することが可能である．X線源と被写体の距離を近づけた場合，平行化すると像の拡大を防げるが，平行化しないと像が拡大してしまうことをコンピュータシミュレーションで証明した(図6)．

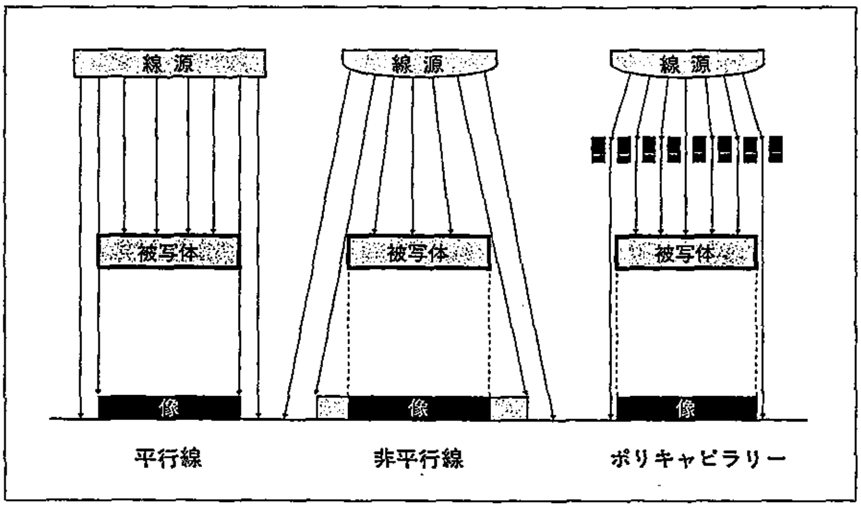

図5．平行化
平行線では被写体と像は同一の大きさであるが(左)，非平行線では像が拡大し，辺縁はぼやける(中)．ポリキャピラリーを用いて平行化させると，像は被写体の大きさに限りなく近づく(右)．

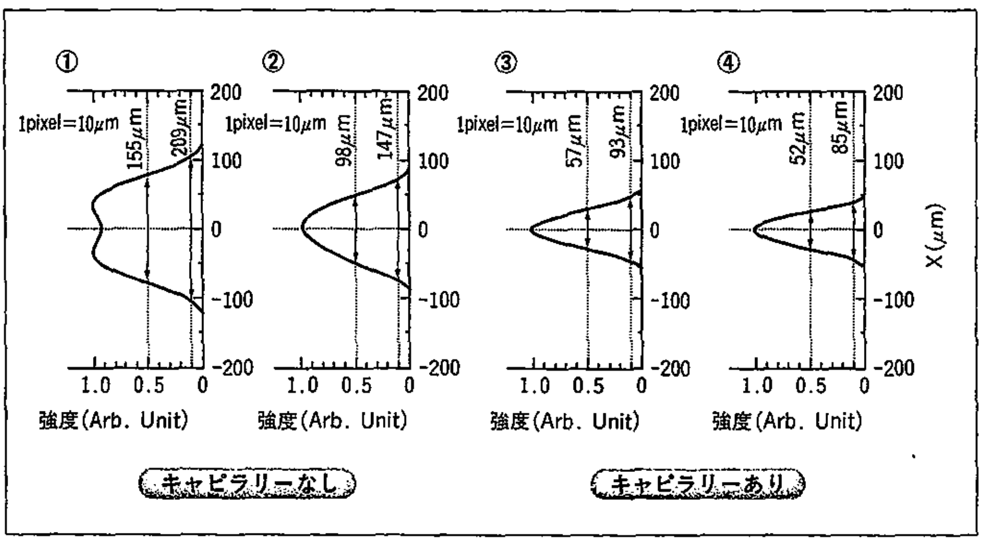

図6．ポリキャピラリーのコンピュータシミュレーション
①②は線源とスリットとの距離がそれぞれ50 cmと80 cmで，キャピラリーによる平行化がない状態である．この時に検出器に入るX線幅は，それぞれ155 μm，98 μmに拡大される．③④も同じく距離を50 cmと80 cmとし，キャピラリーで平行化した状態である．平行化した場合は，52～57 μm程度の誤差しかない．
1 pixel＝10 μm．

4．高解像度・高感度

検出器の解像度をチャート撮影から得ることができる．1 mm 幅に4本のライン(2ラインペア)を識別できれば1,000 μm÷4で250 μmの解像度，同じく20本のライン(10ラインペア)識別できれば50 μmの解像度となる．既存の血管造影装置では約2ラインペアであり，空間分解能は250 μmといえる(図7)．感度を高くすると微量のX線を検出できるため，微小血管を造影するにはイメージングプレートとして高感度蛍光板の使用が好ましい．

病院設置型微小血管造影装置

新エネルギー・産業技術開発機構(NEDO)の支援により，病院設置型微小血管造影装置を開発した．X線源は既存の大容量大出力を持つCT用のX線管を用い，検出系はNHKエンジニアリングの技術により超高感度ハイビジョンカメラシステムを導入した．

1．X線管球

普及型微小血管造影装置のCT用のX線管は，最大陽極熱容量が5 MHUと世界最大級の大きさである．X線高電圧装置も大出力化し，市販の装置では不可能な70 kVp・800 mAで高輝度のX線を得ることができる．連続20秒照射が可能であり，撮影は動画で観察できる．優れた冷却性能を持ち，480秒の休止で繰り返し照射が可能である．

2．疑似単色化

疑似単色化はランタノイド系の金属を複合したフィルターで，ヨードのK吸収端(33.3 keV)上にピークを持つ疑似単色X線を得ることができる．

3．平行化

焦点に起因するボケを低減する目的で，マルチファイバーからなるコーン型のコリメーターを開発した．チャンネルサイズと素子の厚みにより，出射角と透過効率が決定されるため，実用となる条件を求め試作した(図8)．これにより，被写体が検出器から離れる場合に生じる解像度の低下を防ぐことができる．

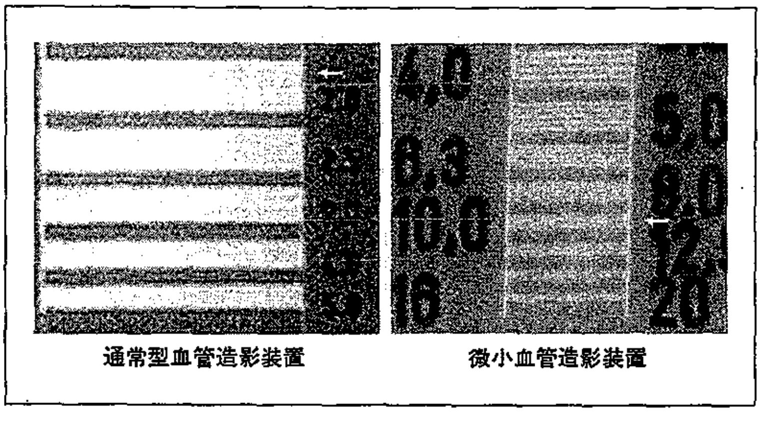

図7．チャートによる解像度の評価
通常型血管造影装置(左)の解像度は250 μm(1 mm/4=2ラインペア)，普及型微小血管造影装置(右)の解像度は50 μm(1 mm/20=10ラインペア)を示す．

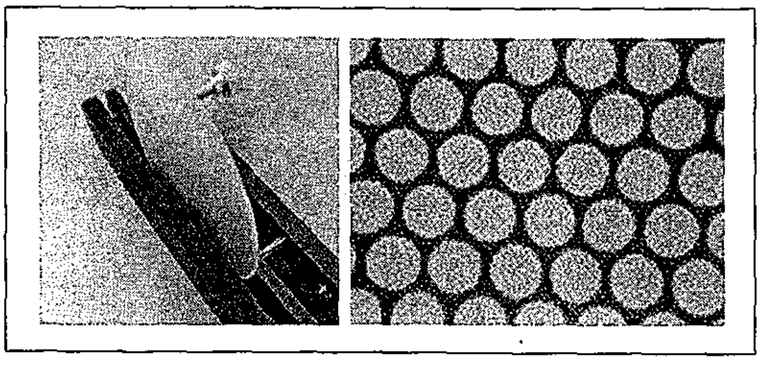

図8．ポリキャピラリー
多数の孔を持ったポリキャピラリーが，X線を平行化する．

4．超高感度ハイビジョンカメラの開発

検出系は高解像度・高感度蛍光板で作成した蛍光像を，超高感度・高精細撮像管であるアバランシェ型ハイビジョンモノクロ新 Super-HARP カメラで撮影する．これらの検出器系から高解像度(50 μm)が得られる．CCD を用いたハイビジョンカメラは，画素あたりの光子数が減少し感度が低下するため，高精細画像として微小血管を描出するには限界がある．アバランシェ型ハイビジョン用撮影管は高解像度で，高感度の撮影が可能である．非セレン膜で構成された光伝導電層は，高電圧操作下で電子なだれ現象を生じさせ，実効量子効率が数百倍の光電変換ができる．新 Super-HARP カメラは，空間分解能は 25 μm で，CCD カメラより 100 倍以上の感度があり，25 μm の非セレン膜の構造をとっている[6)-9)]．

5．トータルシステム

本装置は，既存の血管装置と同様に C アーム保持型を有しており，さまざまな角度からの撮影が可能である(図 9)．今までのハイビジョン映像は，高画質 200 万画素の動画映像 1 秒間 30 フレームを長時間記録する装置が必要であり，放送局用の VTR しかなかった．これは，専門家しか扱えなく，装置から得られた画像の分析も複雑であった．そこで，デジタル高精細画像処理・表示装置を導入した．ハードディスクへの直接記録方式をとり，数十分の長時間記録が可能となり，小型で安価な装置となった．性能は，10 ビットデジタル画像データが記録できる大容量ハードディスク 144GB(1,000×1,000 画素×10 ビットを 30 フレーム/秒を 40 分記録可能)を搭載しており，映像データは直ちに再生・逆再生・スチル再生が可能であり，マウスのみで機械操作ができる．

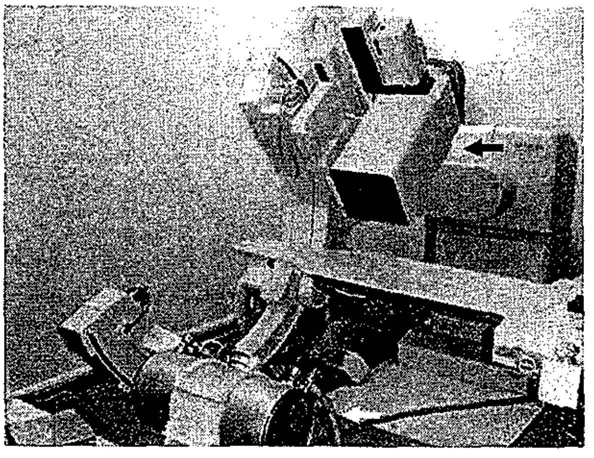

図 9．トータルシステム
筒型の X 線管は，現在臨床で使用されている CT 用の高出力線源である(白矢印)．C アーム上端には蛍光板を有した検出器と HARP 管を有するカメラを搭載している(黒矢印)．

6．直接 X 線量と散乱線量

安全性の検討として，直接 X 線量と散乱 X 線量を計測した．X 線発生装置から 1 m に検出器を設置し，管電圧 70 kV，管電流 500 mA で 20 秒照射した場合，0.547 Sv(62.7R)であった(図 10)．検査の撮影条件としては，最低でも一検査あたり 100 R 以下(3 R/sec)を目標としており，妥当な線量と考えられる．また，X 線発生装置から 1 m の距離にファントムを置き，50 cm 側方で散乱 X 線を検出した場合の散乱 X 線量は 0.0225 mSv(2.58 mR)であった(図 11)．放射線医療従事者の年間被曝量の限度は 50 mSv であり，術者に対する影響は少ないと考えられた．

7．微小血管画像

イヌ冠動脈ファントムを用い，既存の血管造影装置と比較した．ファントムは冠動脈にヨードを含むマイクロスフィアーを注入後に結紮し，作成した．微小血管造影装置では，イヌ冠動脈の中隔枝が末梢まで分岐するたびに血管径が細くなっていくのが観察できたが，既存の X 線装置では観察できなかった(図 12)．また，ウサギ下肢血管を結紮し，慢性期に形成された新生血管を微小血管造影装置で観察した．さらに，血管拡張剤であるアデノシンを動脈に投与したところ，微小血管が拡張する現象も確認できた(図 13)．現在のとこ

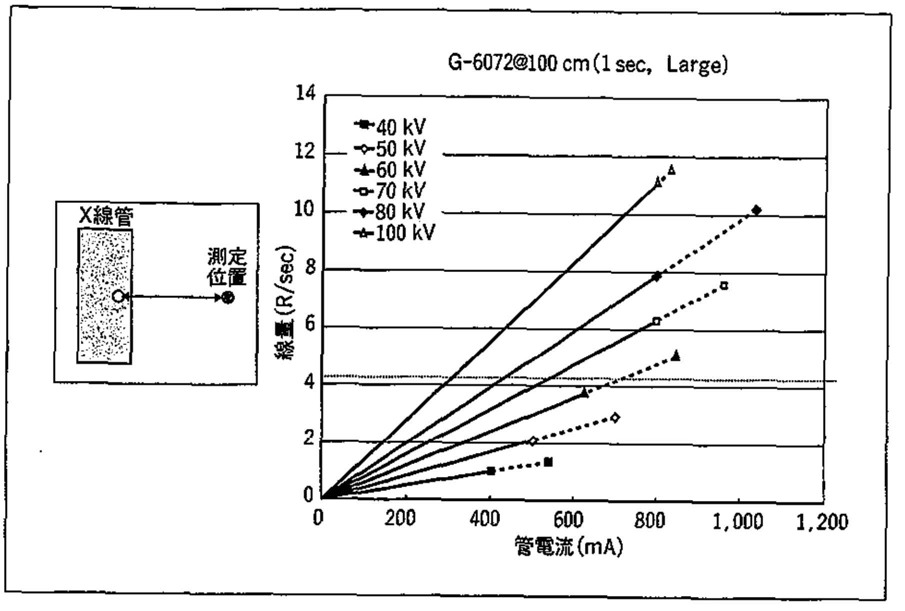

図 10. X 線強度
微小血管造影装置の X 線強度は管電圧 70V，管電流 500mA の 20 秒照射で 0.547 Sv (62.7 R) であった．

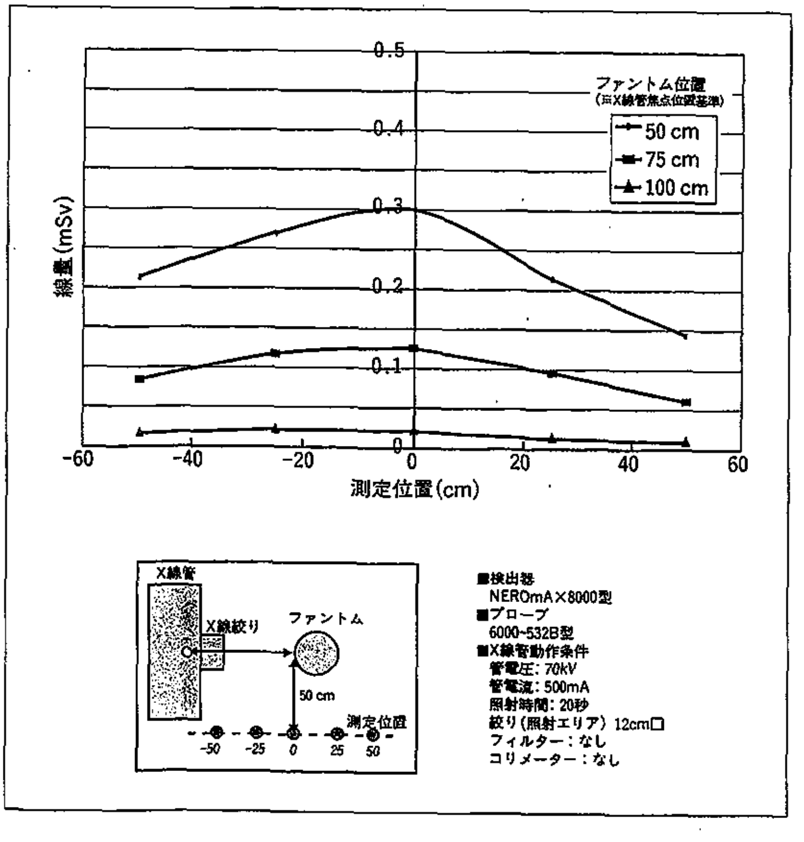

図 11. 散乱 X 線
X 線発生装置から 1 m の距離にファントムを置き，50 cm 側方での散乱 X 線量は 0.0225 mSv (2.58 mR) であった．

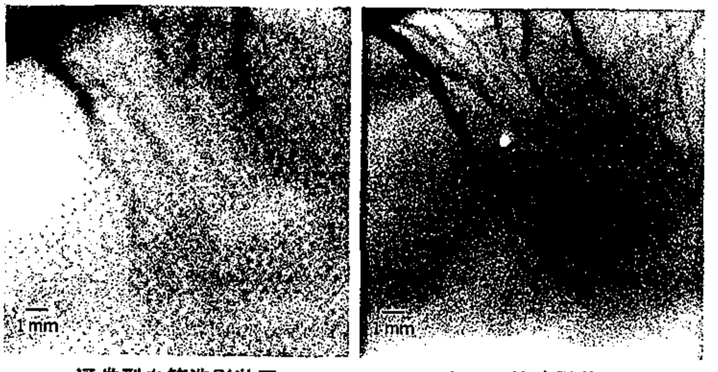

図 12．イヌ冠動脈
通常型血管造影装置ではイヌ冠動脈の末梢側はぼやけてしまっているが(左)，微小血管造影装置では末梢側までイヌ冠動脈末梢を観察することができる(右)．

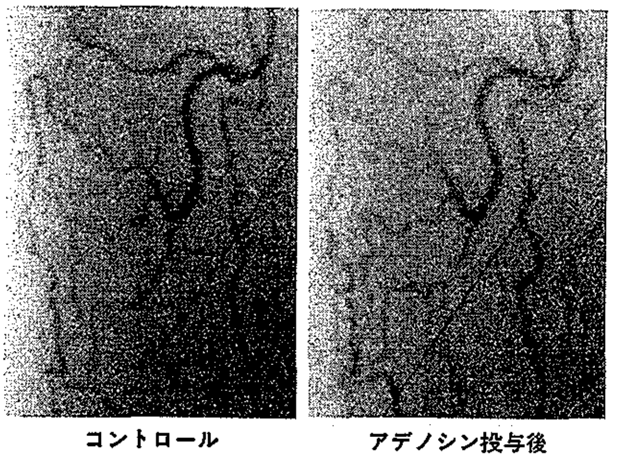

図 13．ウサギ下肢血管
新生血管を微小血管造影装置で観察した(左)．血管拡張剤であるアデノシンを動脈に投与し，微小血管が拡張する現象が観察できた(右)．

ろ，体厚が約 10 cm 程度の被写体しか通過できないため，心血管系など厚い被写体を撮影することはできない．このため，下肢血管病変に対する血管再生療法の効果判定を目的としている．

まとめ

骨髄単核球移植または末梢血幹細胞による血管再生療法の評価に関しては，一般の検査では臨床症状の改善を十分に評価できておらず，適切に再生血管の臨床評価をする方法は確立されていない．今回開発された病院設置型の微小血管造影装置は，高輝度の X 線源と高解像度・高感度の検出器を持ち合わせており，微小血管を鮮明に描出することが可能である．再生治療の前後で微小血管の変化を検討し，血管新生が臨床症状の改善に関与していることを証明できると考えられる．

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原子核研究

Conventional enhanced K-edge angiography utilizing cerium x-ray generator

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Abstract

The cerium-target x-ray tube is useful in order to perform cone-beam K-edge angiography because $K\alpha$ rays from the cerium target are absorbed effectively by iodine-based contrast media. The maximum tube voltage and current were 65 kV and 0.40 mA, respectively, and the focal-spot sizes were approximately 1×1 mm. Sharp cerium $K\alpha$ lines were left using a barium sulfate filter, and the x-ray

intensity was 16.8 μGy/s at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.40 mA. Angiography was performed using iodine-based microspheres 15 μm in diameter. In angiography of non-living animals, we observed fine blood vessels of 100 μm or less.

1. Introduction

Synchrotrons generate monochromatic parallel x-ray beams using single crystals. These beams with photon energies of approximately 35 keV have been employed to perform enhanced K-edge angiography,[1-3] since the beams are absorbed effectively by iodine-based contrast media.

In order to perform high-speed medical radiography, although several different flash x-ray generators[4-9] utilizing cold-cathode tubes have been developed, plasma flash x-ray generators[10-13] are useful to produce quasi-monochromatic x rays without using a K-edge filter. Therefore, we have performed a demonstration of cone-beam K-edge angiography[14] utilizing a cerium plasma generator, since K-series characteristic x rays from the cerium target are absorbed effectively by iodine. Recently, we have developed a steady-state x-ray generator utilizing a cerium-target tube, and have demonstrated enhanced K-edge angiography utilizing a barium sulfate filter.[15] In this research, Kα lines (34.6 keV) were left by absorbing Kβ lines (39.2 keV).

In the present research, we describe a preliminary study on cone-beam K-edge angiography achieved with cerium Kα rays using a barium sulfate filter.

2. Generator

Figure 1 shows the block diagram of the x-ray generator, which consists of a main controller, a cerium-target x-ray tube unit with a Cockcroft-Walton circuit and an insulation transformer, and a personal computer. The tube voltage, the current, and the exposure time can be controlled by both the controller and the computer. The main circuit for producing x rays is illustrated in Fig. 2, and employs the Cockcroft-Walton circuit in order to decrease the dimensions of the tube unit. In the x-ray tube, the negative high-voltage is applied to the cathode electrode, and the anode (target) is connected to the tube unit case (ground potential) to cool the anode and the target effectively. The filament heating current is supplied by an AC power supply in the controller in conjunction with an insulation transformer. In this experiment, the tube voltage applied was from 45 to 65 kV, and the tube current was regulated to within 0.40 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. Monochromatic Kα lines were left using a 5-mm-thick barium sulfate filter in which barium sulfate powder was mixed with polymethyl methacrylate (PMMA) resin, since both the bremsstrahlung and the Kβ rays were absorbed effectively by the filter. In designing the filter, the surface density of the barium sulfate powder is important, since the x rays are absorbed effectively by the powder as compared with the PMMA resin. In this case, the density was approximately 10 mg/cm^2.

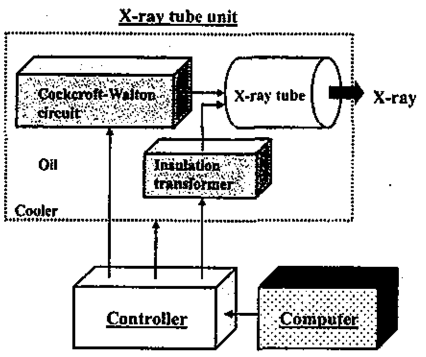

Fig. 1: Block diagram of compact x-ray generator with cerium-target tube.

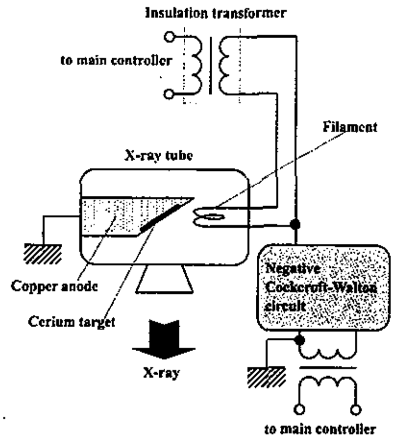

Fig. 2: Main circuit of x-ray generator.

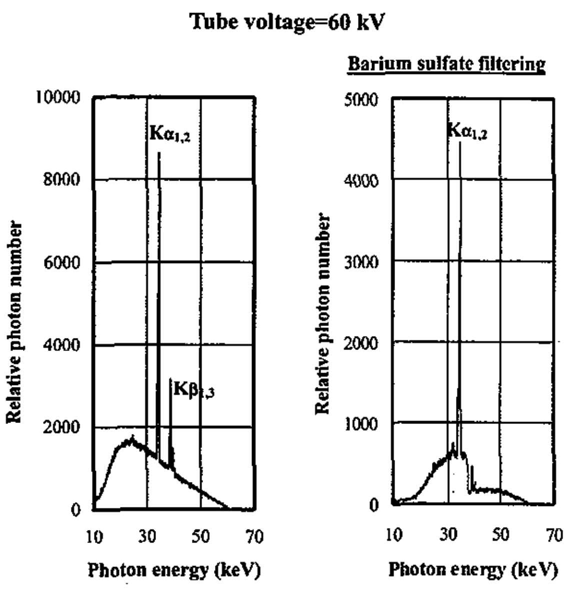

Fig. 3: X-ray spectra measured using germanium detector and filter.

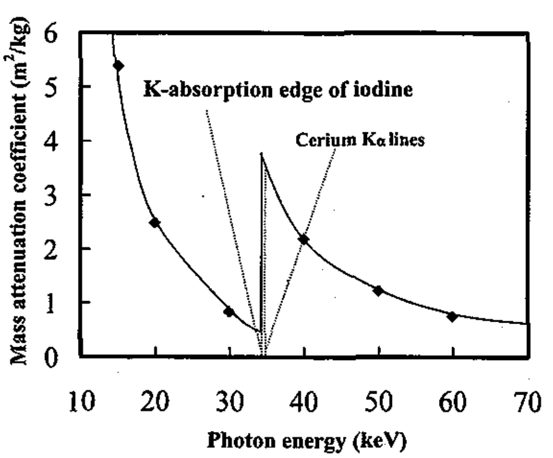

Fig. 4: Mass attenuation coefficients of iodine, and average photon energy of cerium Kα lines.

3. Characteristics

The x-ray intensity rate was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source. At a constant tube current of 0.40 mA, the x-ray intensity increased when the tube voltage was increased. In this measurement, the intensity with a tube voltage of 60 kV and a current of 0.40 mA was 16.8 μGy/s with errors of less than 0.2%.

In order to measure images of the x-ray source, we employed a pinhole camera with a hole diameter of 50 μm in conjunction with a Computed Radiography (CR) system[16] with a sampling pitch of 87.5 μm. When the tube voltage was increased, spot dimensions increased slightly and had values of approximately 1×1 mm.

In order to measure x-ray spectra, we employed a germanium detector (GLP-10180/07-P, Ortec Inc.) (Fig. 3). When the tube voltage was increased, the Kα intensity substantially increased, and both the maximum photon energy and the intensities of bremsstrahlung x rays increased.

4. Angiography

Figure 4 shows the mass attenuation coefficients of iodine at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The average photon energy of the cerium Kα lines is shown just above the iodine K-edge. Cerium is a rare earth element and has a high reactivity; however, the average photon energies of Kα is 34.6 keV, and iodine contrast mediums with a K-absorption edge of 33.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

The angiography was performed using the CR system (Konica Regius 150), iodine microspheres of 15 μm in diameter, and the filter. The distance (between the x-ray source and the imaging plate) was 1.5 m, and the tube voltage was 60 kV. Figure 5 shows angiograms of an extracted dog heart. Because the size of the dog heart is almost the same as human heart, human coronary arteries can be observed.

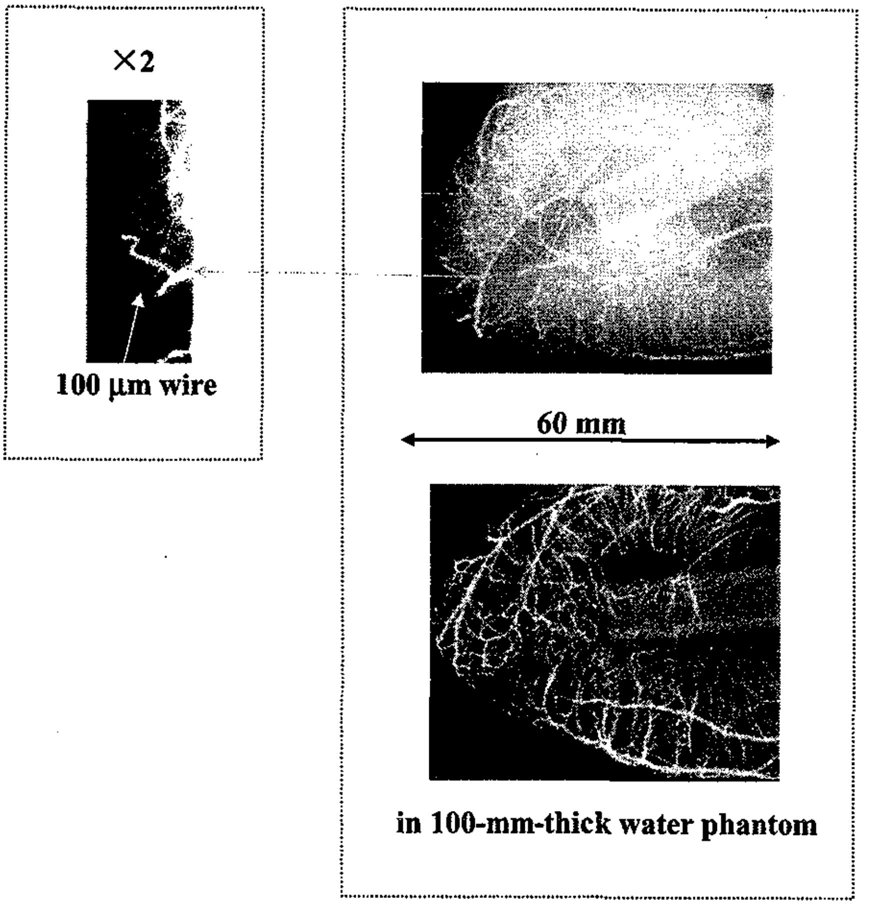

Fig. 5: Angiogram of extracted dog heart using iodine microspheres.

5. Discussion and Conclusions

In summary, we developed a new x-ray generator with a cerium-target tube and succeeded in producing cerium Kα lines, which can be absorbed easily by iodine-based contrast media. Both the characteristic and bremsstrahlung x-ray intensities increased with increases in the tube voltage, and Kβ lines were absorbed effectively by the barium sulfate filter.

In this preliminary experiment, although the maximum tube voltage and current were 65 kV and 0.40 mA, respectively, the voltage and current could be increased. Subsequently, the generator produced maximum number of Kα photons was approximately 3×10^7 photons/cm^2·s at 1.0 m from the source, and the photon count rate can be increased easily by improving the target.

Acknowledgment

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原子核研究

Preliminary experiment for producing higher harmonic x rays utilizing copper plasma triode

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Abstract

In the plasma flash x-ray generator, a 200 nF condenser is charged up to 50 kV by a power supply, and flash x rays are produced by the discharging. The x-ray tube is a demountable triode with a trigger electrode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Target evaporation leads to the formation of weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target, and intense Kα lines are left using a 10-μm-thick nickel filter. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 15 kA. The K-series characteristic x

rays were clean and intense, and higher harmonic x rays were observed. The x-ray pulse widths were approximately 700 ns, and the time-integrated x-ray intensity had a value of approximately 20 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

1. Introduction

Recently, soft x-ray lasers have been produced by a gas-discharge capillary,[1-4] and the laser pulse energy substantially increased in proportion to the capillary length. However, it is difficult to increase the laser photon energy to 10 keV or beyond. Because there are no x-ray resonators in the high-photon-energy region, new methods for increasing coherence will be desired in the future.

To perform high-speed soft radiography, several different flash x-ray generators[5-10] have been developed corresponding to specific objectives. Subsequently, we have developed a compact flash x-ray generator utilizing a disk-cathode demountable diode,[11,12] and have performed a preliminary experiment for producing clean characteristic x rays utilizing angle dependence of bremsstrahlung x rays.

With recent advances in high-voltage pulse technology, several different plasma flash x-ray generators have been developed corresponding to specific radiographic objectives, and a major goal in our research is the development of an intense and sharp monochromatic x-ray generator that can impact applications with biomedical radiography.

In this paper, we describe a plasma flash x-ray generator[13-15] utilizing a rod-target radiation tube, used to perform a preliminary experiment for generating intense and clean K-series characteristic x rays and their higher harmonic x rays by forming a linear copper plasma cloud around a fine target.

2. Generator

Figure 1 shows a block diagram of the high-intensity plasma flash x-ray generator. This generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 200 nF, a turbomolecular pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. The high-voltage main condenser is charged to 50 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode with the trigger device. The plasma flash x rays are then produced.

The x-ray tube is a demountable cold-cathode triode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa. This tube consists of the following major parts: a hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a brass focusing electrode, a trigger electrode made from copper wire, a stainless steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped copper target 3.0 mm in diameter with a tip angle of 60°. The distance between the target and cathode electrodes is approximately 20 mm, and the trigger electrode is set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by the focusing electrode, evaporation leads to the formation of a weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x rays (Fig. 2). The plasma then transmits the fluorescent rays easily, and bremsstrahlung rays with energies lower than the K-edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, intense characteristic x rays are generated from the plasma-axial direction.

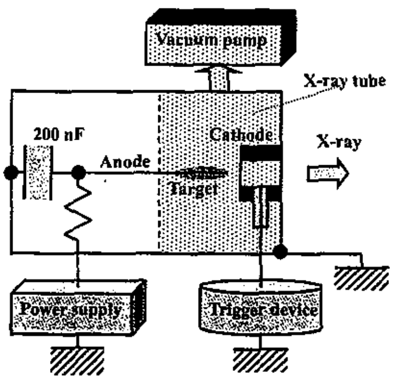

Fig. 1: Block diagram including electric circuit of plasma flash x-ray generator.

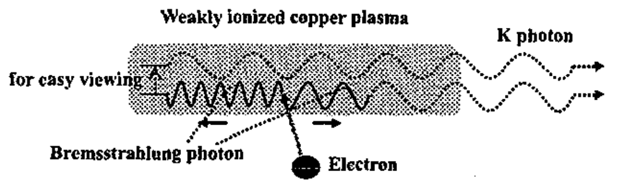

Fig. 2: K-photon irradiation from plasma.

3. Characteristics

Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was approximately 15 kA.

X-ray output pulse was detected by a combination of a plastic scintillator and a photomultiplier using a 10-μm-thick nickel filter. The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 700 ns, and the time-integrated x-ray intensity per pulse measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 utilizing MSO-S elements without energy compensation) had a value of about 20 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

X-ray spectra from the plasma source were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[16] (Konica Regius 150) with a wide dynamic range, using the filter, and relative x-ray intensity was calculated from Dicom digital data. Figure 3 shows measured spectra from the copper target with a charging voltage of 50 kV. In fact, we observed clean K lines such as lasers, and Kα lines were left by absorbing Kβ lines using the filter. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage, and higher harmonic x rays were observed.

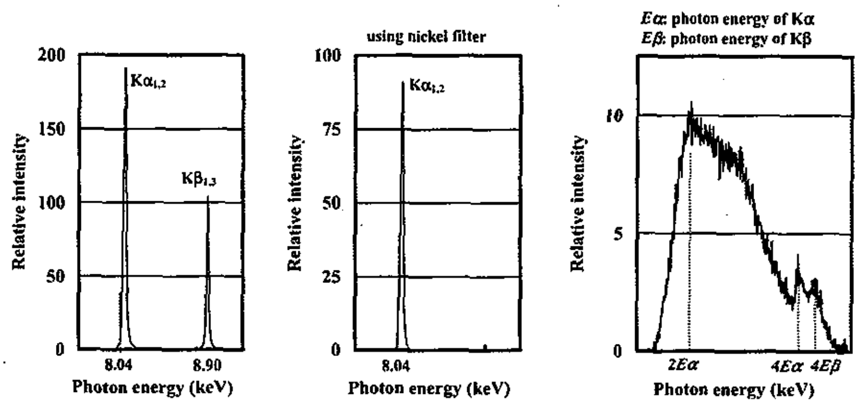

Fig. 3: X-ray spectra from weakly ionized copper plasma at indicated conditions.

4. Radiography

The plasma radiography was performed by the CR system using the filter. The charging voltage and the distance between the x-ray source and imaging plate were 50 kV and 1.2 m, respectively.

Firstly, an image of plastic bullets falling into a polypropylene beaker from a plastic test tube is shown in Fig. 4. Because the x-ray duration was about 1 μs, the stop-motion image of bullets could be obtained. Figure 5 shows an angiogram of a rabbit ear; iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 50 μm were visible.

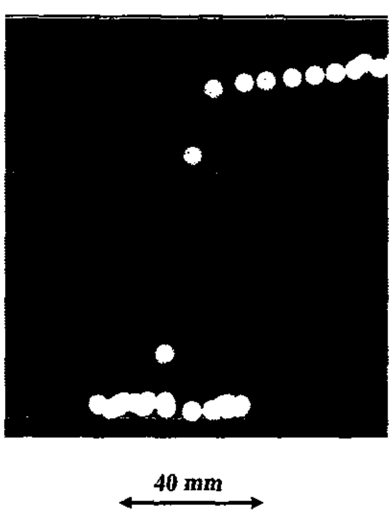

Fig. 4: Radiogram of water falling into polypropylene beaker from plastic test tube.

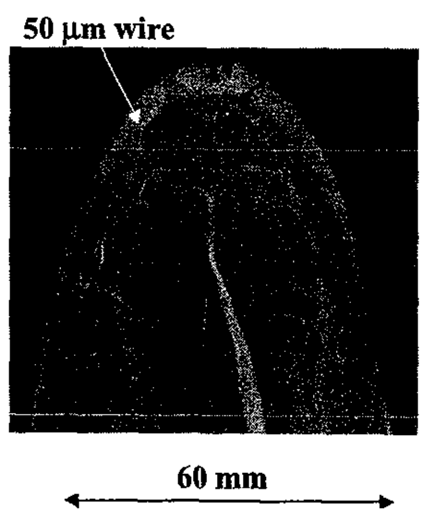

Fig. 5: Angiograms of rabbit ear.

5. Discussion and Conclusions

Concerning the spectrum measurement, we obtained fairly intense and clean K lines from a weakly ionized linear plasma x-ray source, and Kα lines were left by absorbing Kβ lines using the nickel filter. In particular, the higher harmonic x rays were produced from the plasma. Assuming that the harmonic rays are produced by the x-ray resonation (Fig. 6), the estimated spectra are shown in Fig. 7. In cases where a copper target is employed, fractional harmonic x rays are absorbed by an x-ray window and air.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography, and the generator produced number of characteristic Kα photons was approximately 5×10^7 photons/cm^2 at 1.0 m per pulse. In addition, since the photon energy of characteristic x rays can be controlled by changing the target elements, various quasi-monochromatic high-speed radiographies, such as high-contrast angiography and mammography, will be possible.

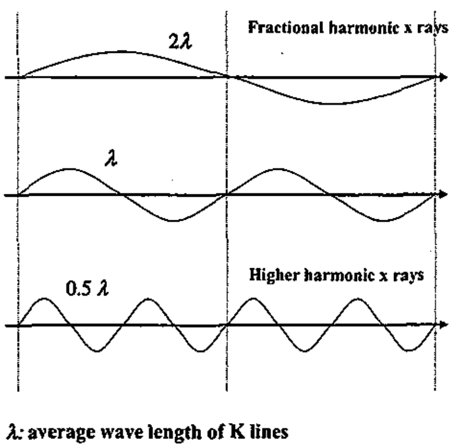

Fig. 6: X-ray resonation without using resonator.

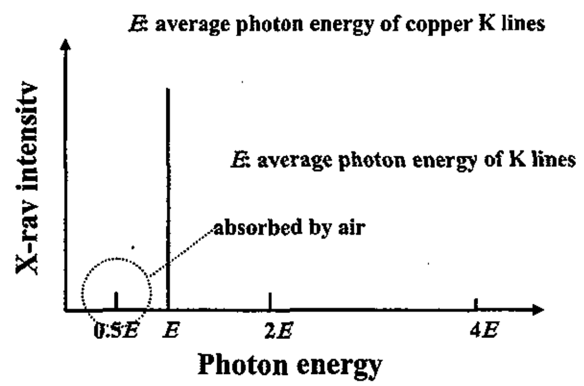

Fig. 7: Estimated x-ray spectra under resonation.

Acknowledgment

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, and 16591222) and Advanced Medical Scientific Research from MECSST, Health and Labor Sciences Research Grants(RAMT-nano-001, RHGTEFB-genome-005 and RHGTEFB-saisei-003), Grants from Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

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