Propagation Phase Contrast Imaging For Angiography

Camilo Rueda Pérez
201815185

Director: PhD Carlos Ávila B.

Physiscs Department
Science Faculty
Universidad de los Andes

Introduction

- Imaging from X-rays is of great importance today
- 1895 - Wilhelm Röntgen
- Good image quality is related to good diagnoses
- New tecniques as X-Pci have been developed
- These have brought advances in different areas

Figura 1. Mano de la esposa de Wilhelm Röntgen
Imagen tomada de: Röntgen**,** W (1896) *On a new kind of rays.* Science, Vol 111, No. 59

X Ray imaging

X ray attenuation imaging

- Wave intensity decays. It follows Beer-Lambert law (1)

$$I = I_0 e^{-\mu t} \qquad (1)$$

- µ: Linear attenuation coefficient
- *t*: Sample thickness

X Ray imaging

X ray attenuation imaging

(2) $I_1 = I_0 e^{-\mu_1 t_1}$ (3) $I_2 = I_0 e^{-\mu_1 (t_1 - t_2)} e^{-\mu_2 t_2}$

- Contrast attenuation is defined by intensity differences.

(4) $$C_{att} = \frac{I_1 - I_2}{I_1} = 1 - e^{-(\mu_1 - \mu_2) t_2}$$

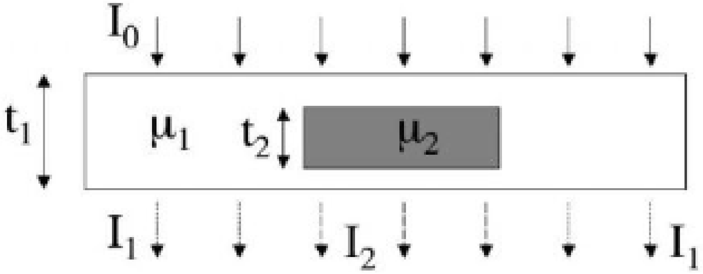


Figura 2. Intensities after passing through samples with different attenuation coefficients and thicknesses.
Image taken from: Olivo, A and Castelli, E. (2014) *X-ray phase contrast imaging: From synchrotrons to conventional sources*, La Rivista del Nuovo Cimento, Vol 37

X Ray imaging

X ray attenuation imaging

- Three dimensión generalization:

$$I(x,y) = I_0(x,y)e^{-(\mu_1^\lambda - \mu_2^\lambda)T_0(x,y)} \tag{5}$$

$$T(x) = 2\sqrt{r^2 - x^2} \tag{6}$$

$$I(x,y) = \int I_0(x,y)e^{-(\mu_1^\lambda - \mu_2^\lambda)T_0(x,y)} D(\lambda)d\lambda \tag{7}$$

X Ray imaging

X Ray phase contrast imaging

- Phase shift of X-rays as they pass through a certain sample

(8) $$\Psi_i(\mathbf{r},t) = E_0(\mathbf{r})e^{-i\omega t}$$

- X-rays induce oscillations on electrons

(9) $$f = \frac{-\omega^2}{(\omega^2 - \omega_0^2 - i\Gamma\omega)} = -(f' + f'')$$

X Ray imaging

X Ray phase contrast imaging

- An index of refraction is defined which in turn is complex

(10) $$n = 1 - r_e(N\lambda^2/2\pi)$$

(11) $$n = 1 - \delta + i\beta$$

(12) $$\Phi = \frac{2\pi}{\lambda}\int_{Superficie}\delta(x,y,z)dz$$

(13) $$\mu = \frac{4\pi\beta}{\lambda} = \frac{2\omega\beta}{c} = 2N\lambda r_e f''$$

X Ray imaging

X Ray phase contrast imaging

- The scattered wave will have the form :

$$\Psi_r(\mathbf{r},t) = E_0(\mathbf{r}) exp\left(\frac{2\pi i n l}{\lambda}\right) = \Psi_0 exp\left(\frac{2\pi i \delta l}{\lambda}\right) exp\left(\frac{-2\pi i \beta l}{\lambda}\right) \tag{12}$$

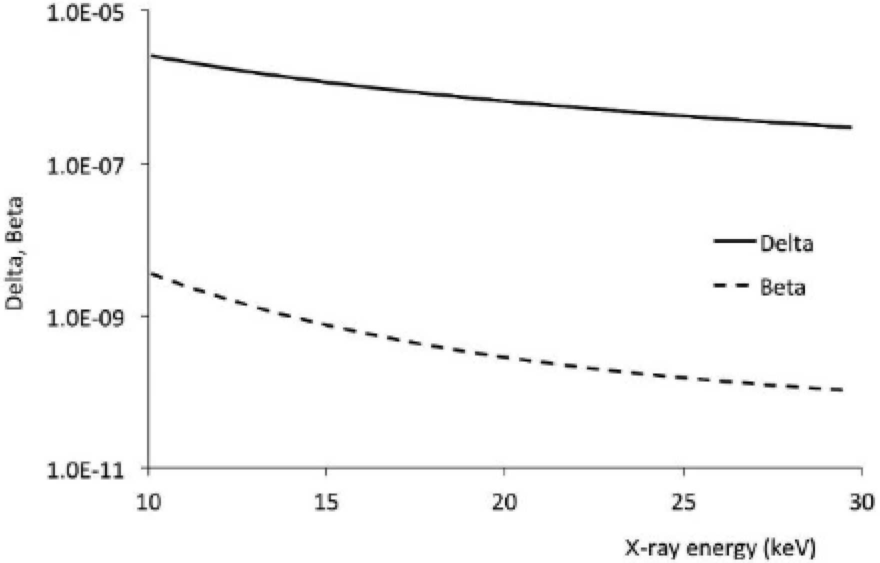


Figura 3. δ and β coefficients in a 10 – 30 keV energy range for PMMA.
Image taken from: Olivo, A and Castelli, E. (2014) *X-ray phase contrast imaging: From synchrotrons to conventional sources*, La Rivista del Nuovo Cimento, Vol 37

X Ray imaging

X Ray phase contrast imaging

- An increased intensity is detected on the edges of the sample

- A new contrast is defined:

$$(13) \quad C_{fase} = \frac{I_{max} - I_{min}}{I_{Background}}$$

$$(14) \quad CNR = \frac{I_{Max} - I_{Background}}{\sigma_{Background}}$$

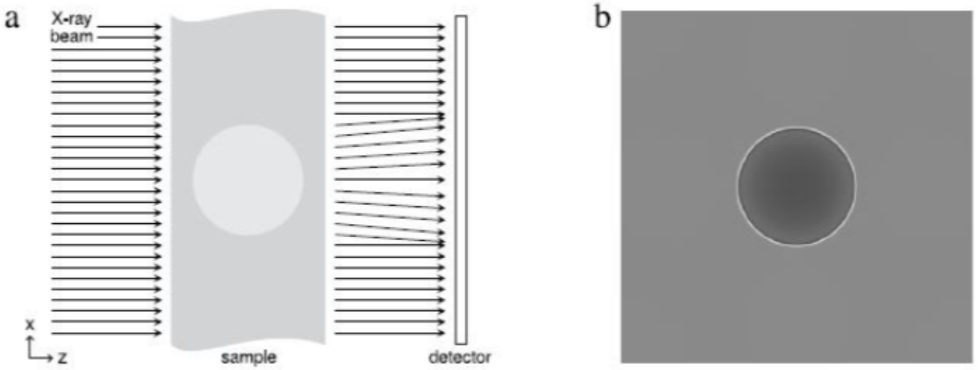


Figura 4. XRPCi Representation: (a) Sample plane (b) Image obtained represented as an intensity distribution. Image taken from: M. Endrizzi. (2017) *X-ray phase contrast imaging*, Nuclear Inst. and Methods in Physics Research, Vol 878

XPCi Methods

There are 5 main methods to execute XPCi

These are:

- Interferometry method
- Free-space propagation/ propagation based imaging/ In line Pci
- Analyzer based imaging (Diffraction Enhanced imaging)
- Grating based imaging
- Tracking based methods

Some others derive from these, like Edge Illumination

Free space propagation

- Easier and cheaper way to execute XPCi
- Requires a great space between sample and detector
- The greater the space, the greater the phase shift effects
- Intensity changes are given by phase shifts

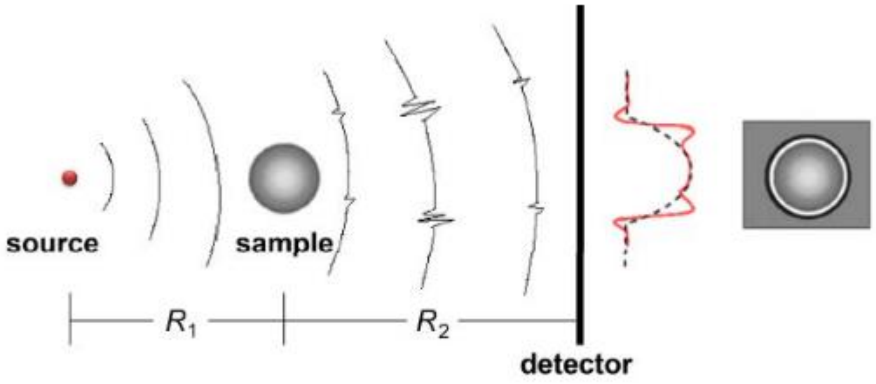


Figura 9. In-Line Pci squematic representation. Image taken from: X. Guo et al (2011) *Improving image qualityof x-ray in-line phase contrast imaging using an image restoration method*, Optic Express, Vol 19, No 23

Free space propagation

- Intensity distribution in (x,y) plane is given by:

(15) $$I(x,y,M,\lambda) = \frac{I_0}{M^2}\left(1 + \frac{R_2\lambda}{2\pi M}\nabla^2\phi(x,y,R_1,\lambda)\right)$$

(16) $$M = \frac{R_1 + R_2}{R_1}$$

- A high spatial coherence is required

(17) $$l_c = \frac{\lambda R_1}{\sigma_s 2\sqrt{2log2}}$$

Free space propagation

- Its use dates back to 1995 by Snigrev et al [34].
- Point sources and synchrotron sources have been used [36,37].
- In the investigative part, the following stand out:
  1. Holotomographies [38].
  2. Tomographies [39].
  3. Coronary arteries visualization [44].
  4. Collagen fibers [46].
  5. Rodent lungs [50].
  6. etc

State of Art

XPCi angiography:

In-line holography and phase-contrast microtomography with high energy x-rays

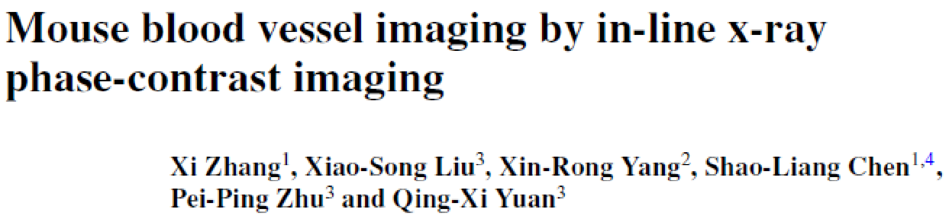
P Spanne, C Raven, I Snigireva and A Snigirev†

European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble Cedex, France

- 5.1 mm external diameter artery.
- Sample at 66 cm from the X ray source.
- Source energy: 28 keV.
- Increased intensity at the edges.

State of Art

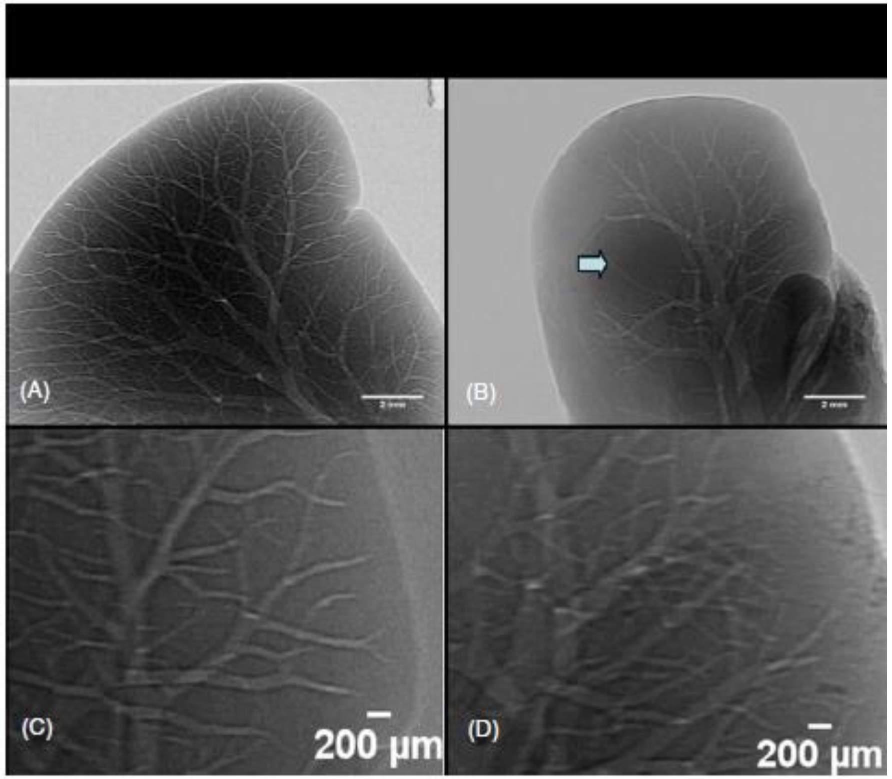
XPCi angiography:



Mouse blood vessel imaging by in-line x-ray phase-contrast imaging

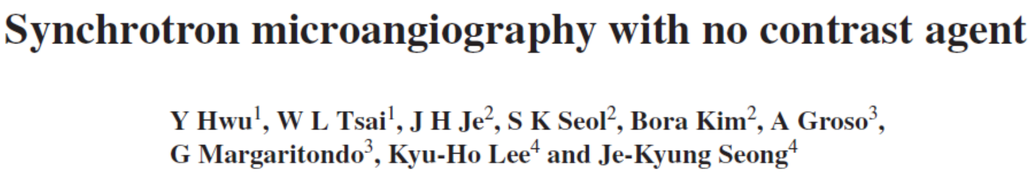
Xi Zhang[1], Xiao-Song Liu[3], Xin-Rong Yang[2], Shao-Liang Chen[1,4],
Pei-Ping Zhu[3] and Qing-Xi Yuan[3]

- Visualization of 200 µm arteries in kidneys.
- Absence of contrast agents.



State of Art

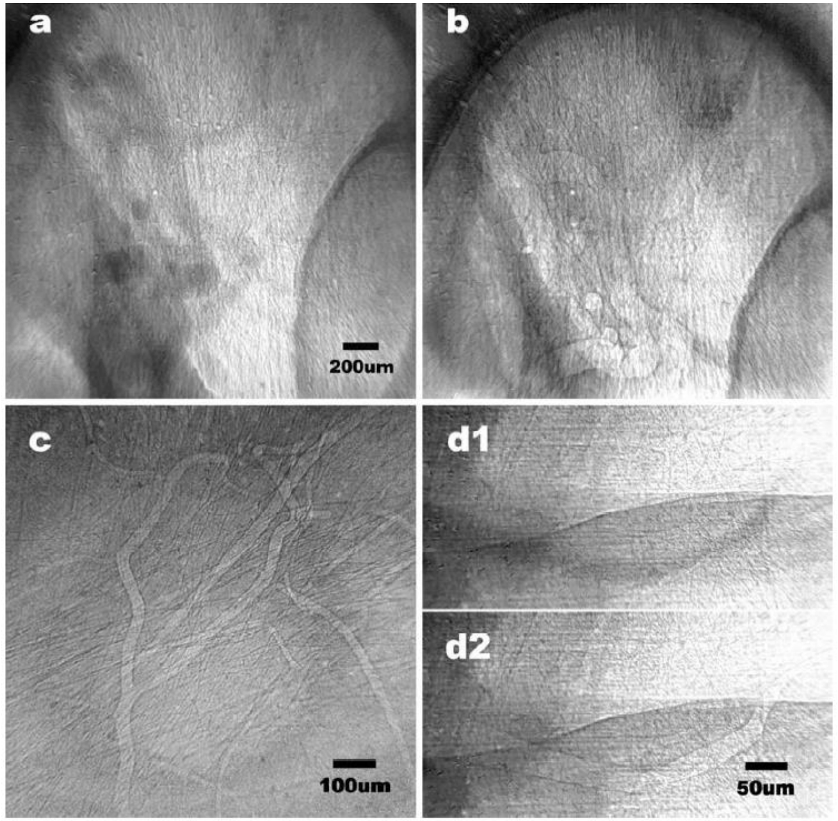
XPCi angiography:



Synchrotron microangiography with no contrast agent

Y Hwu[1], W L Tsai[1], J H Je[2], S K Seol[2], Bora Kim[2], A Groso[3],
G Margaritondo[3], Kyu-Ho Lee[4] and Je-Kyung Seong[4]

- 8 µm arteries
- Presence of contrast agents.



McXtrace

- X Ray simulator
- Based on Monte Carlo (MC) methods
- Quantitative and qualitative data

McXtrace - Monte Carlo Xray Tracing, is a joint venture by

Our code is based on technology from .

Figura 14. McXtrace. Imagen taken from: https://www.mcxtrace.org/

Experimental set-up

- Hamamatsu L6622-01 with colimator
- Medipix 3RXV1
- Sample

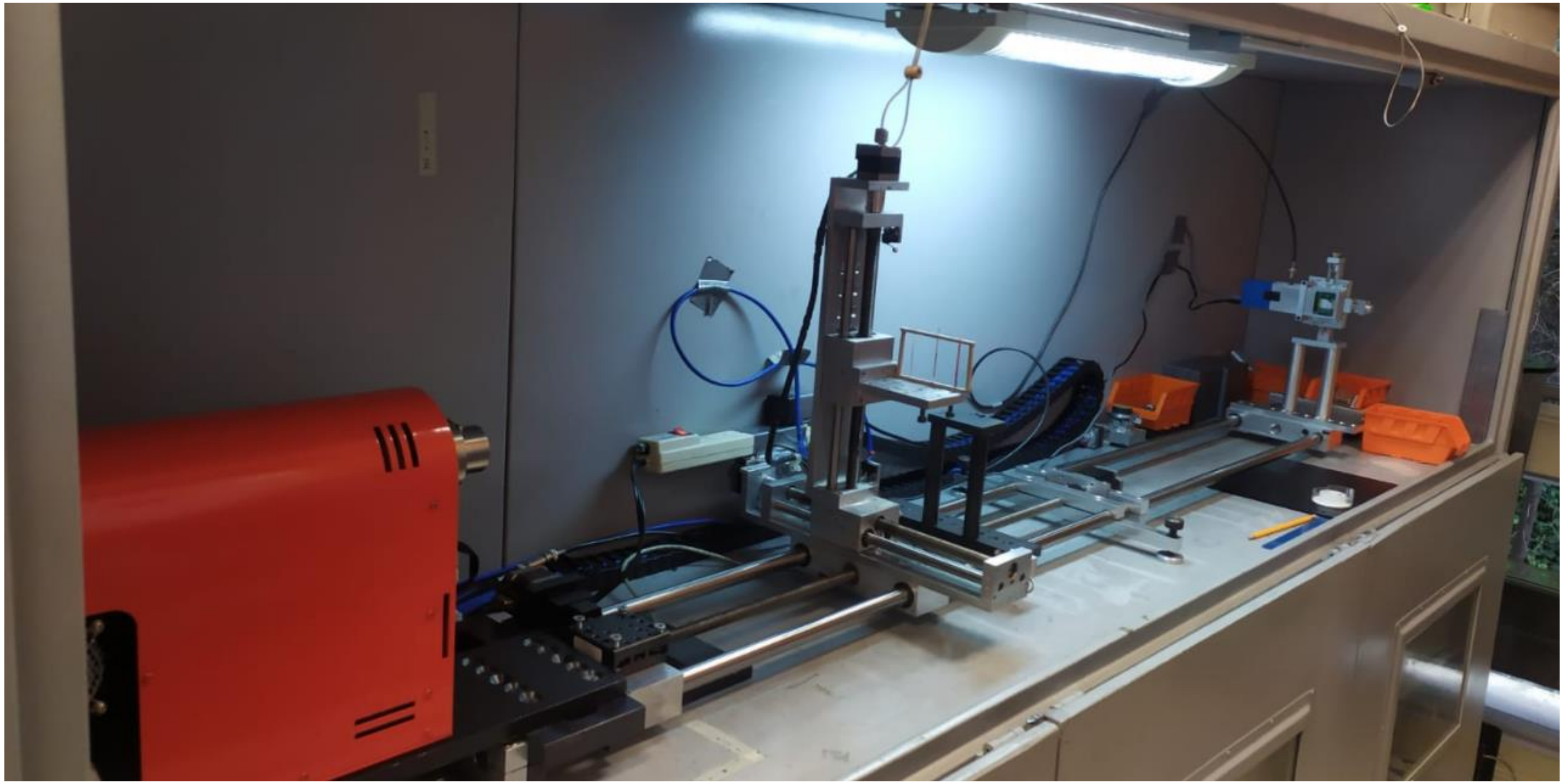


Figura 14. Experimental set-up

Experimental set-up

X Ray detector: Medipix 3RXV1

- Silicon
- 256 x 256 pixels matrix
- 55 µm
- -100 V
- 10 µA
- 1.8 m from the source

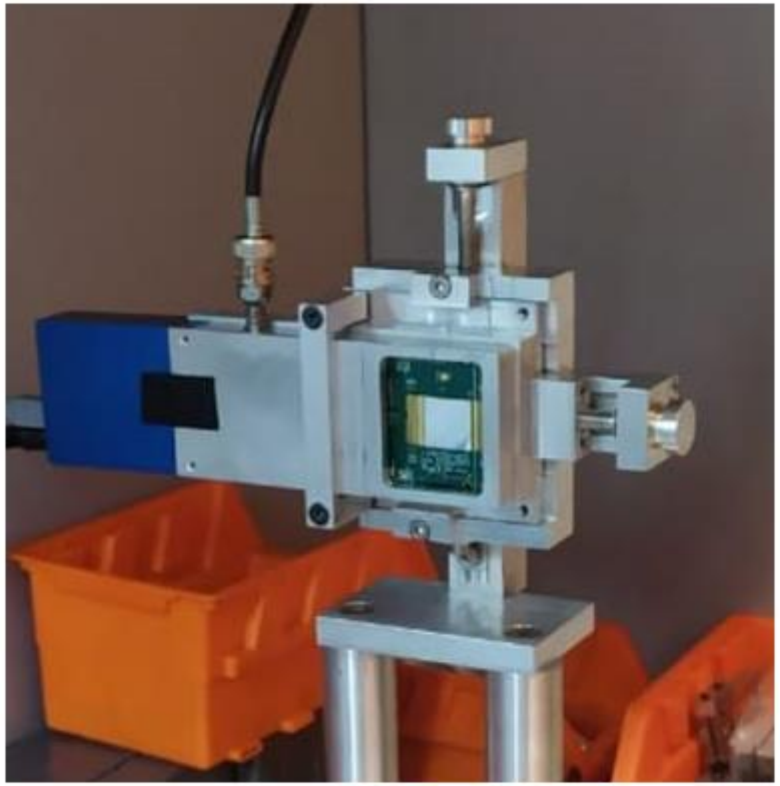


Figura 16 Medipix 3RXV1 X Ray detector

.

Samples

Artificial Sample

- Catheter PVC sample tubes of 1.43, 2.00 and 2.54 mm external diameter
- They have been filled with air, povidone iodine and beef blood
- 0.6 m from the source

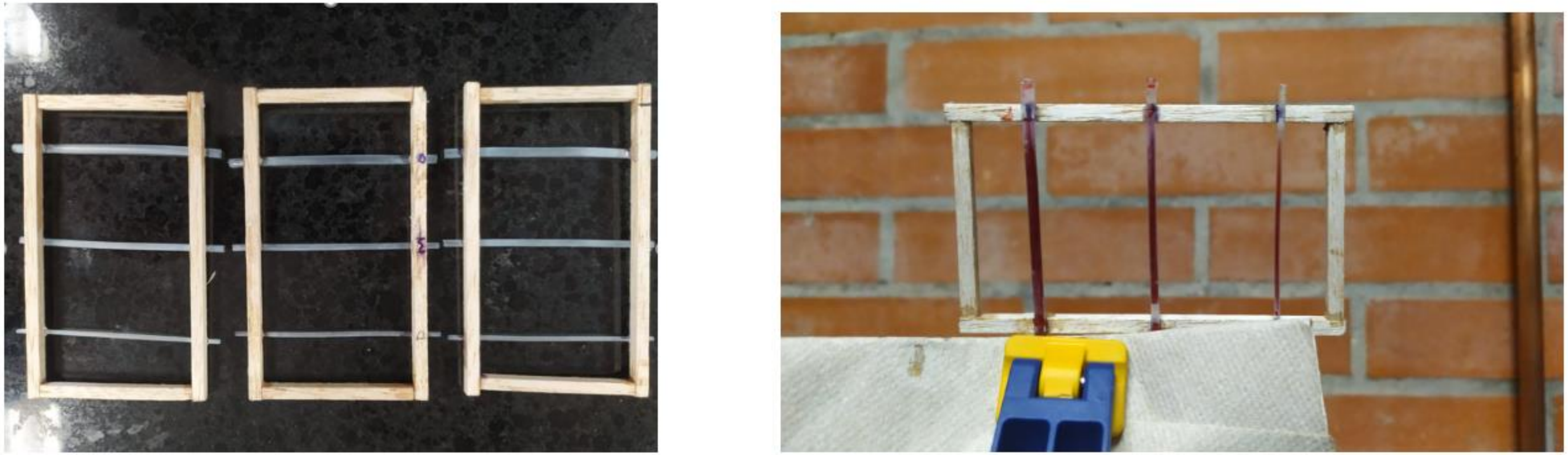


Figura 17. Samples designed for the experimental set-up
.

Samples

Organic Sample

- Pig pulmonary aorta
- Filled with air, povidone iodine and beef blood

- **Figura 18.** Pig pulmonary aorta

Simulated set-up

- X-ray point source
- Pixel matrix as detector
- Sample: Concentric cylinders

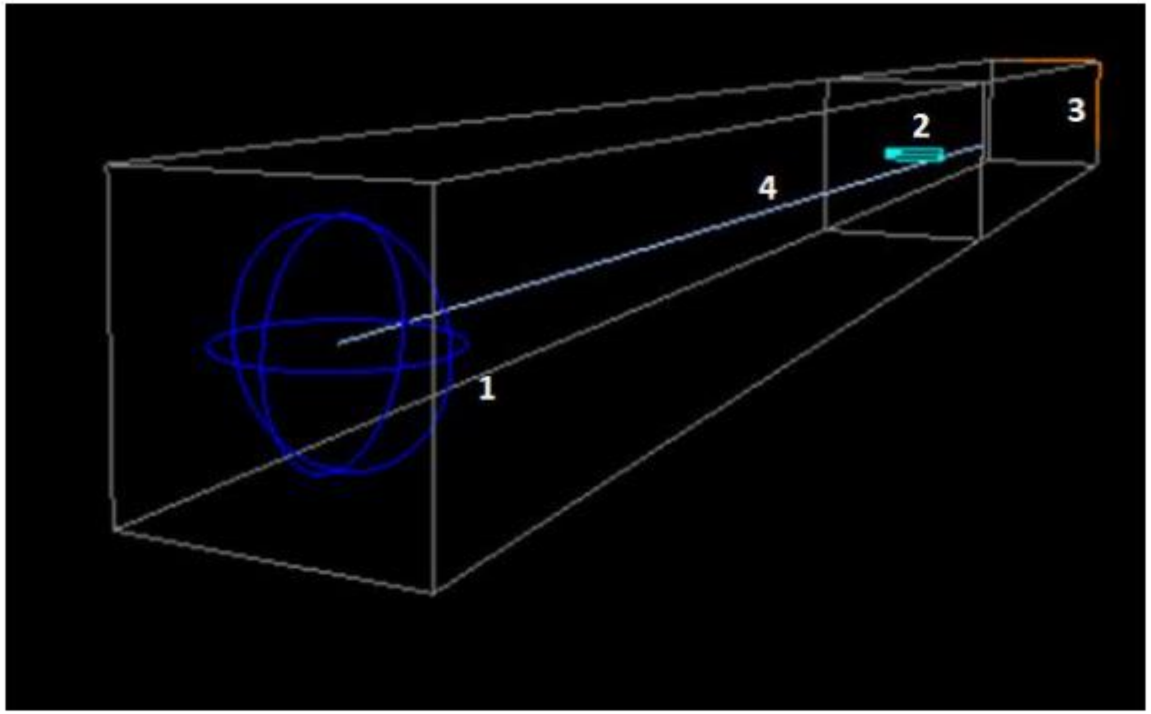
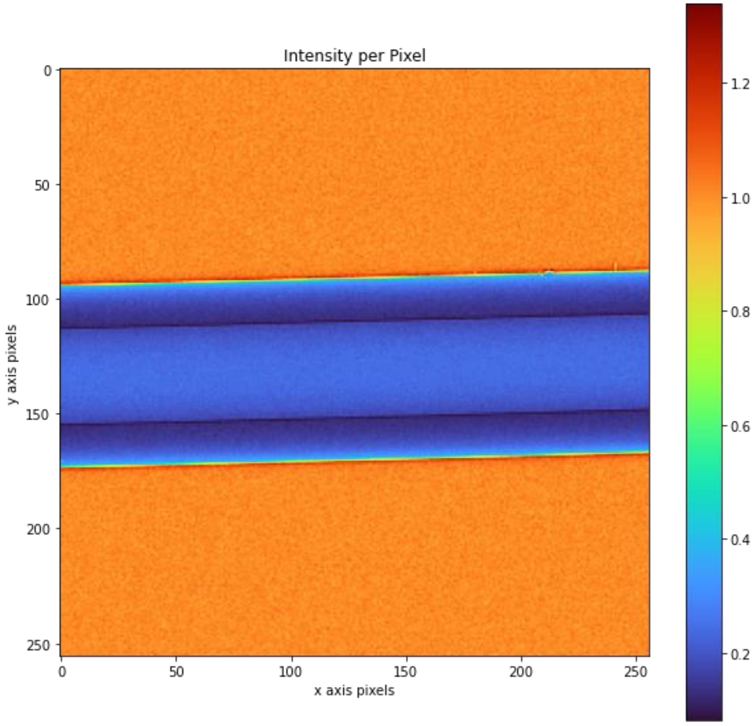


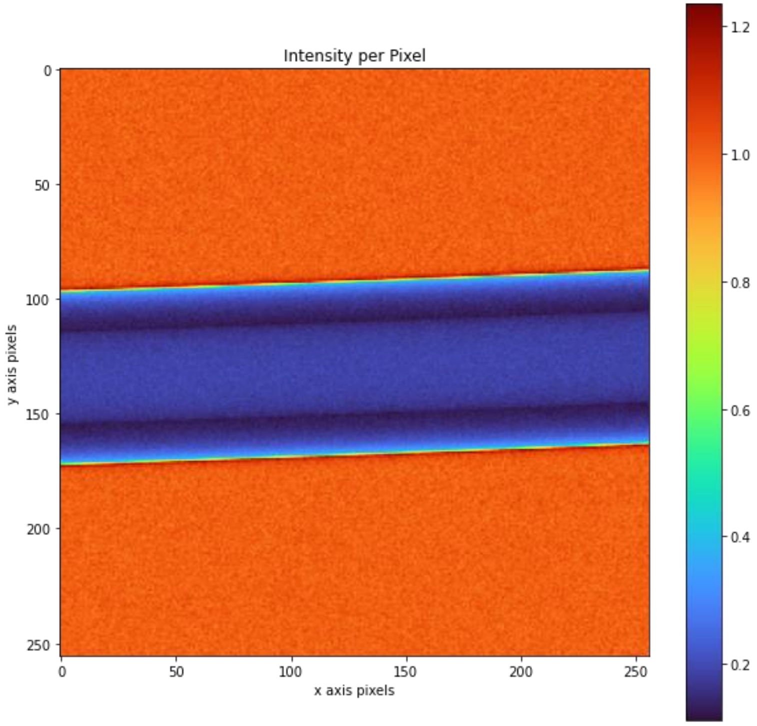
Figura 19. Simulated set-up

Experimental Results

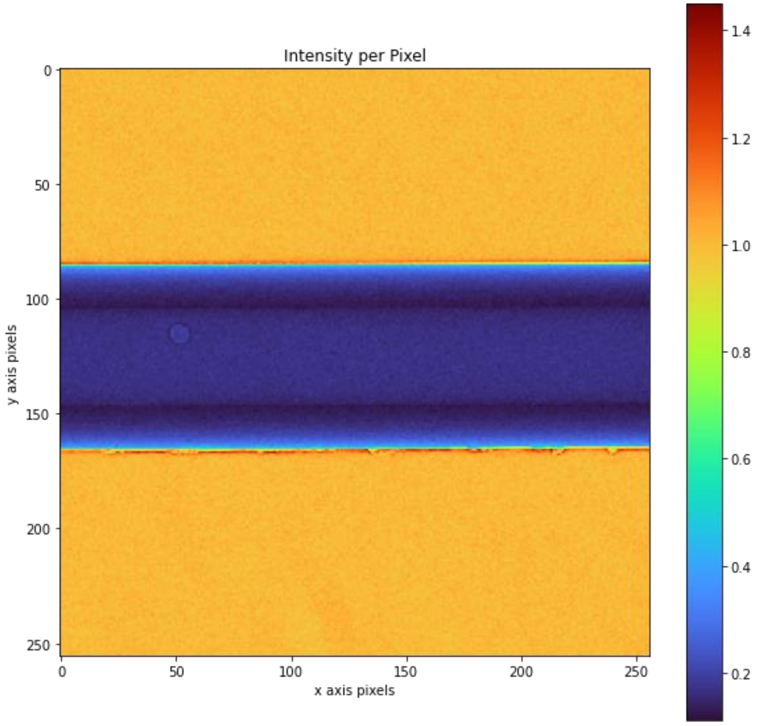
1.43 mm samples



Air



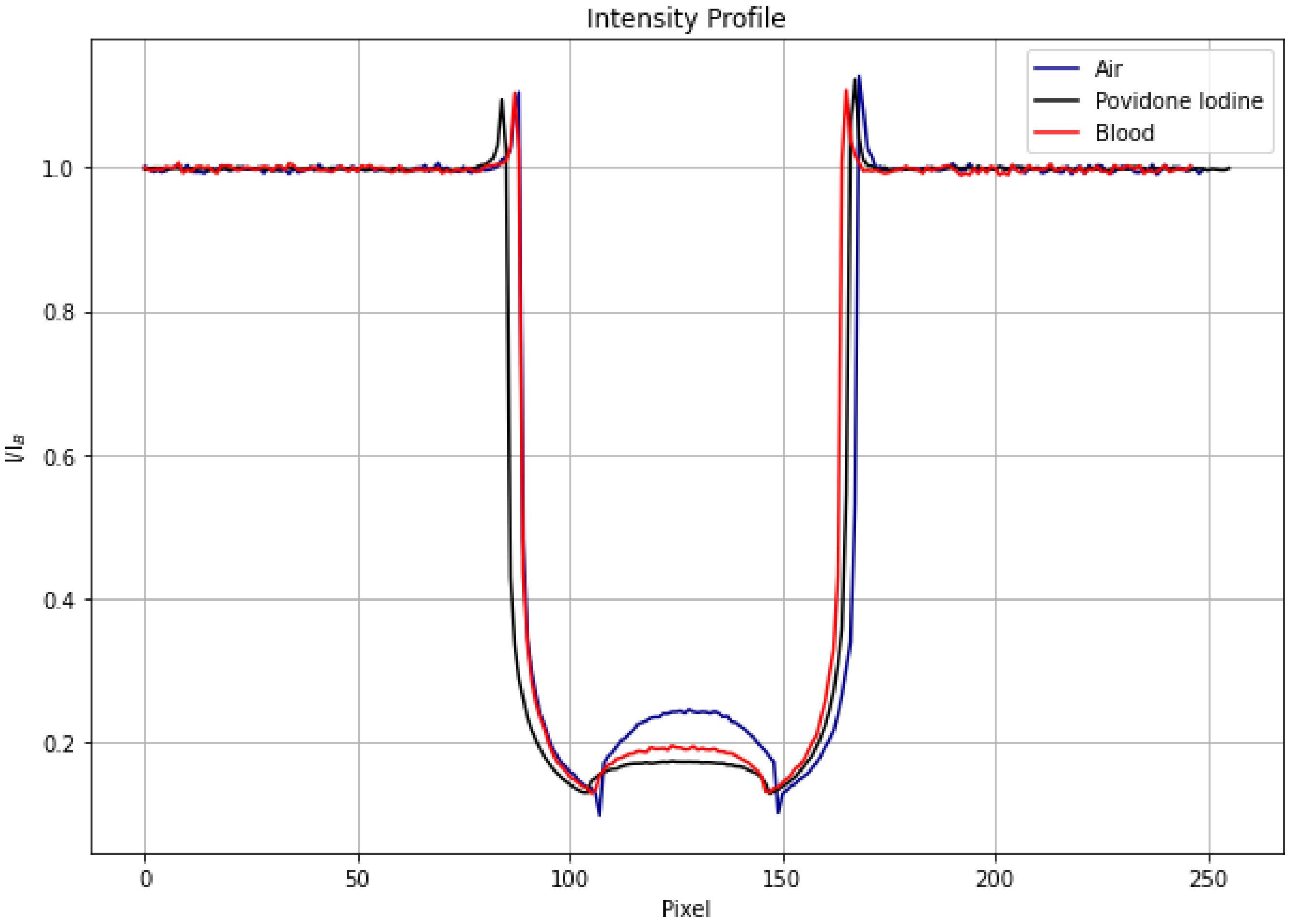
Blood

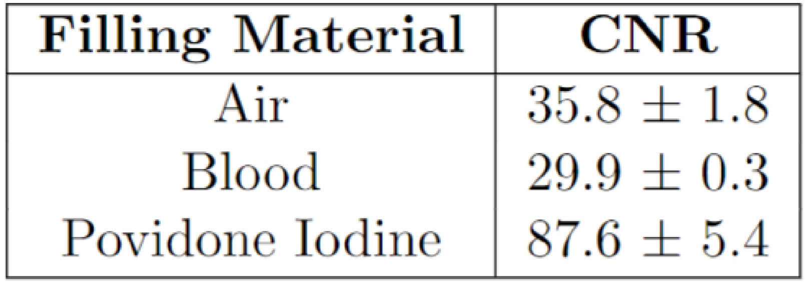


Povidone iodine

Experimental Results

1.43 mm samples

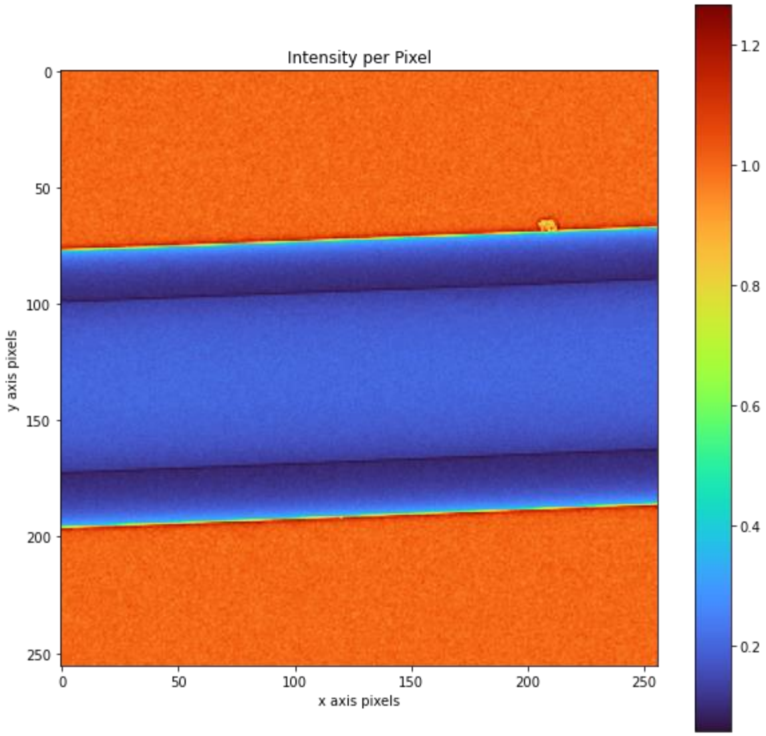




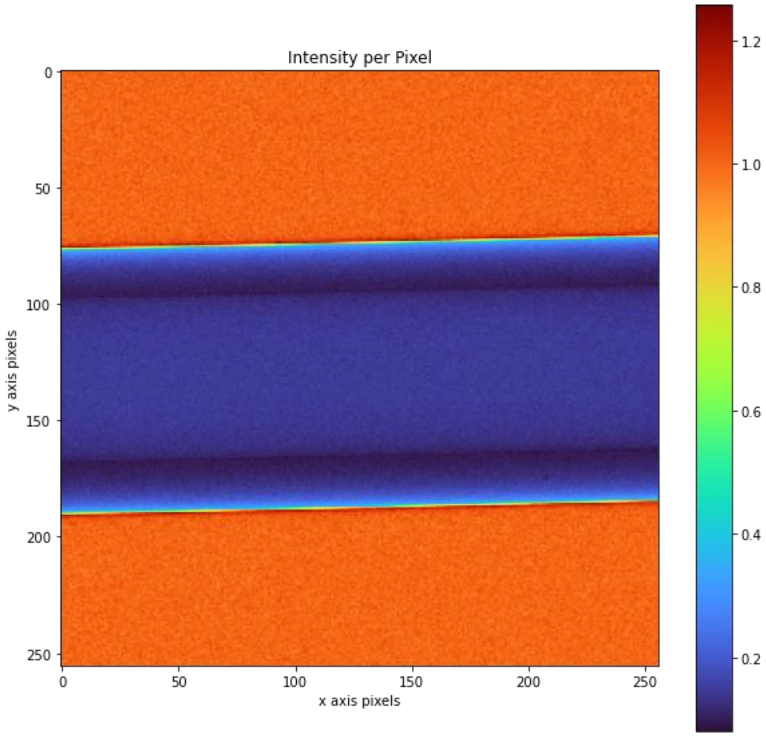
Filling Material	CNR
Air	35.8 ± 1.8
Blood	29.9 ± 0.3
Povidone Iodine	87.6 ± 5.4

Experimental Results

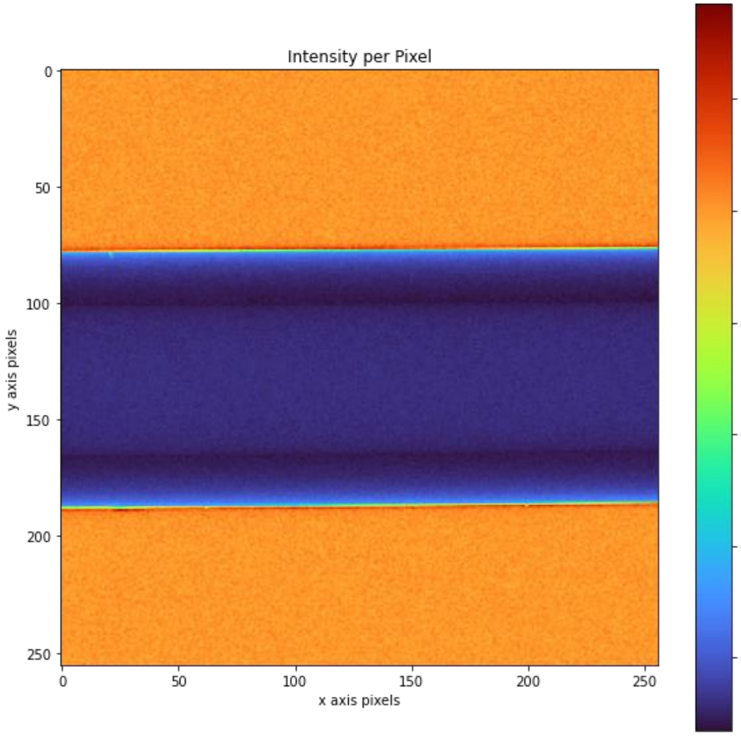
2.00 mm samples



Air



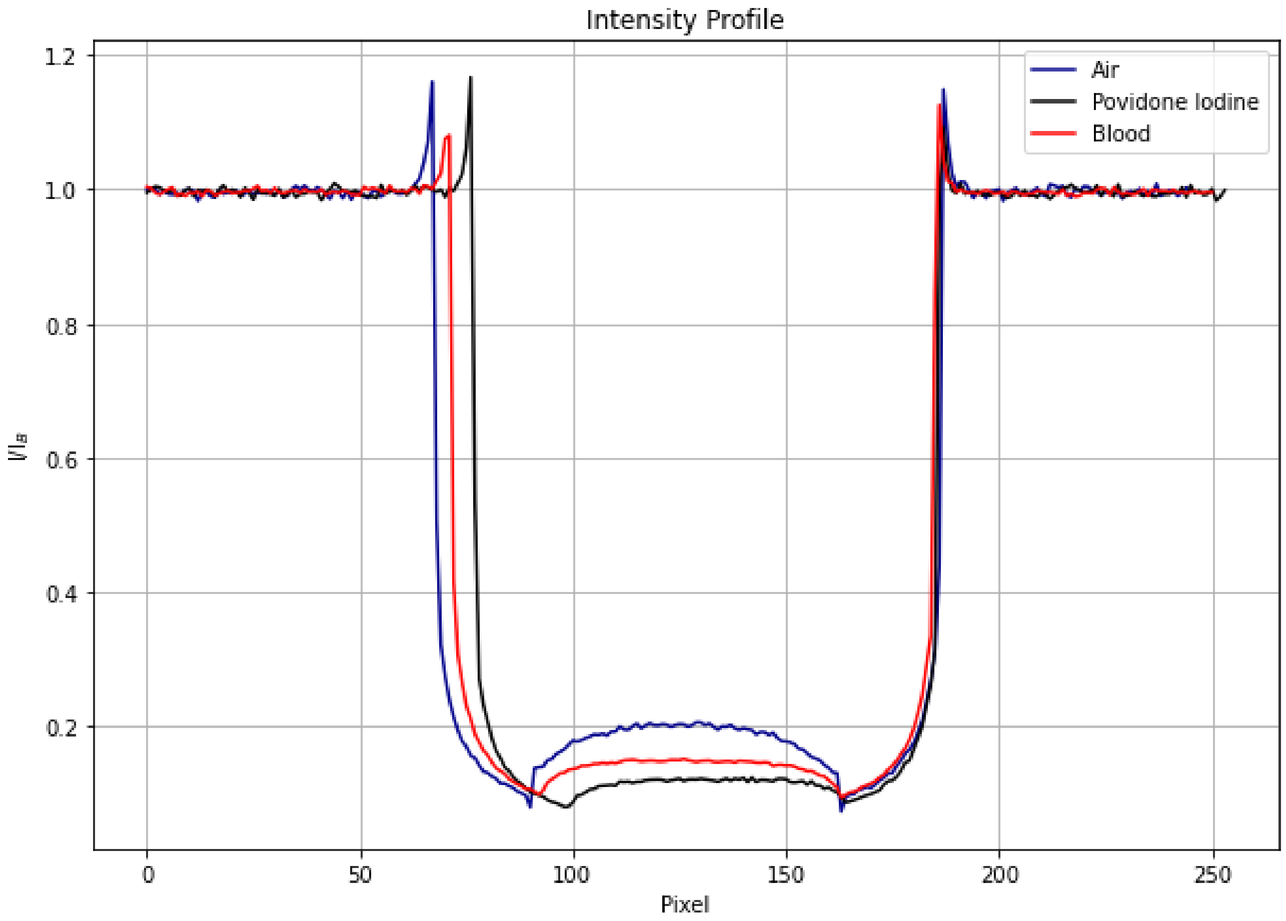
Blood

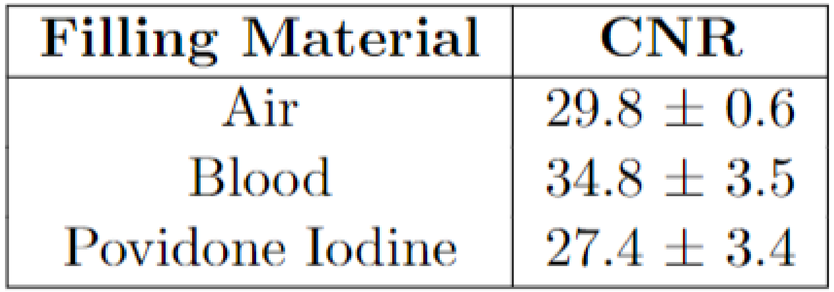


Povidone iodine

Experimental Results

2.00 mm samples

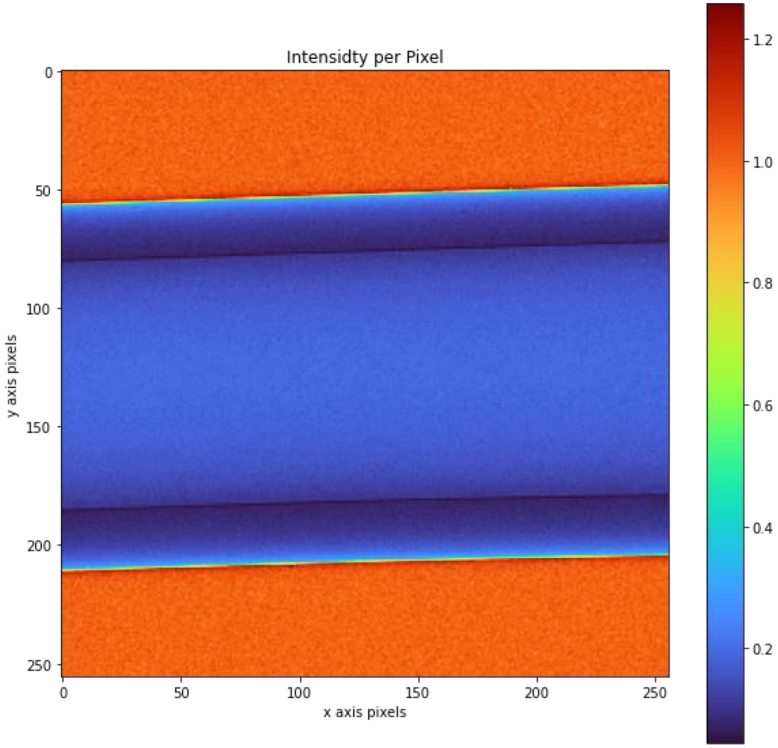




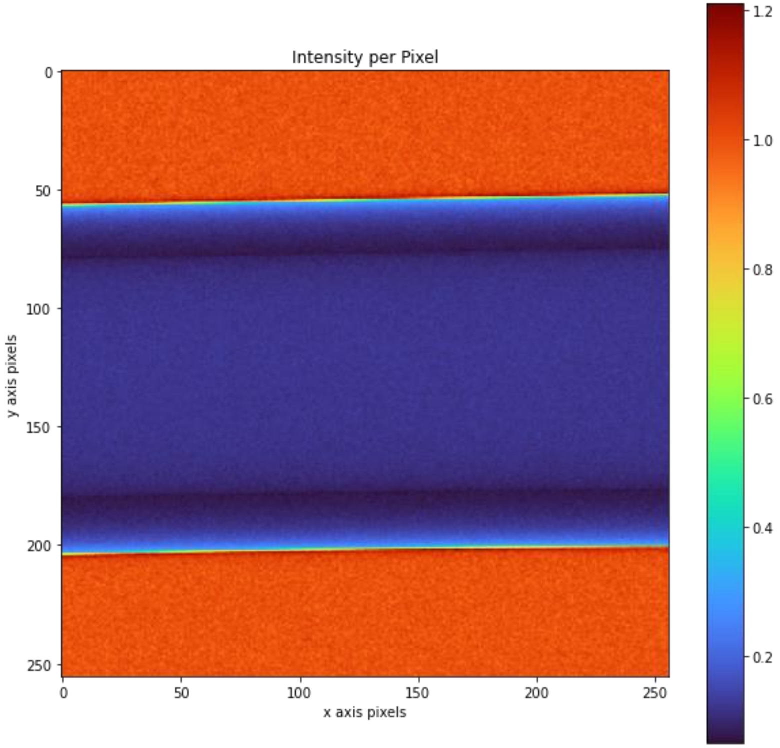
Filling Material	CNR
Air	29.8 ± 0.6
Blood	34.8 ± 3.5
Povidone Iodine	27.4 ± 3.4

Experimental Results

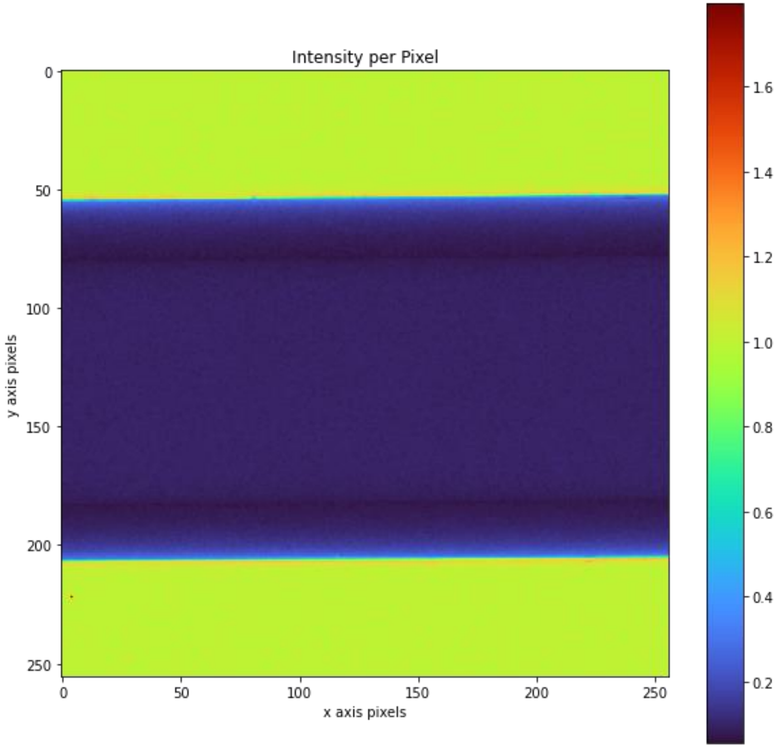
2.54 mm samples



Air



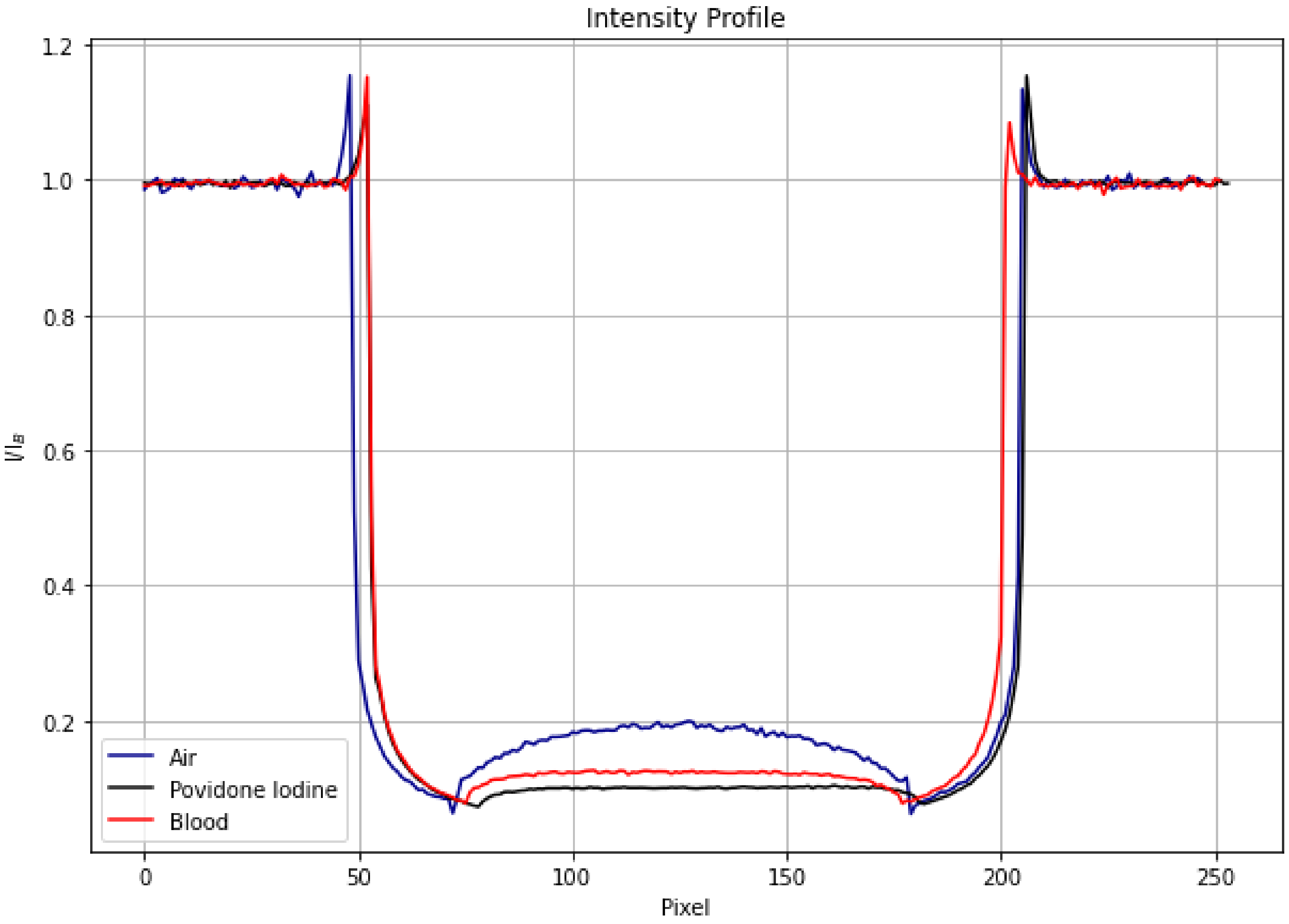
Blood

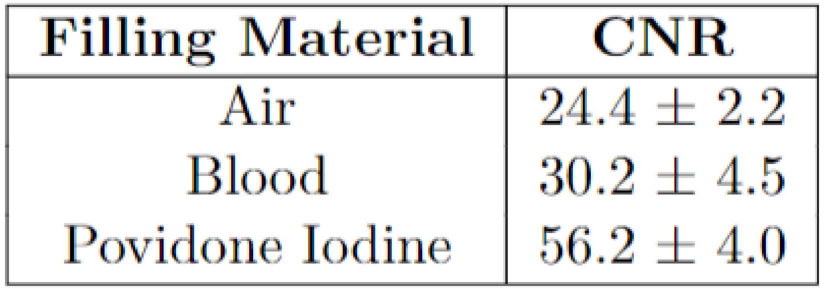


Povidone iodine

Experimental Results

2.54 mm samples

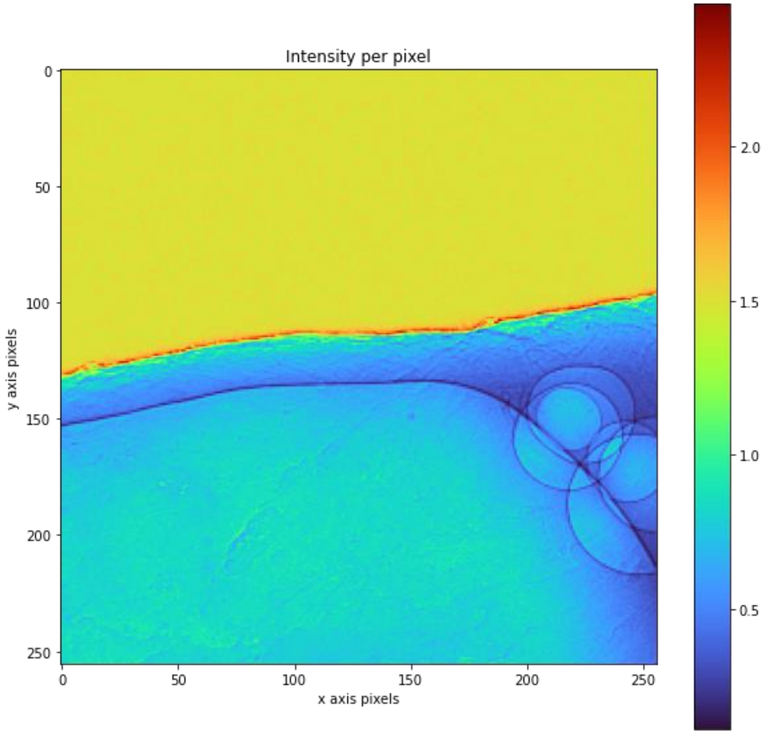




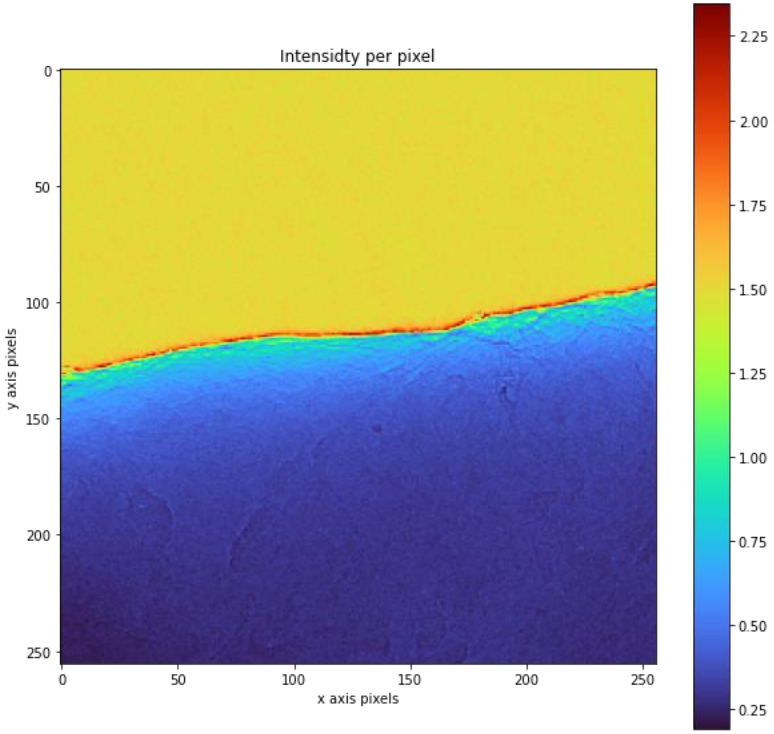
Filling Material	CNR
Air	24.4 ± 2.2
Blood	30.2 ± 4.5
Povidone Iodine	56.2 ± 4.0

Experimental Results

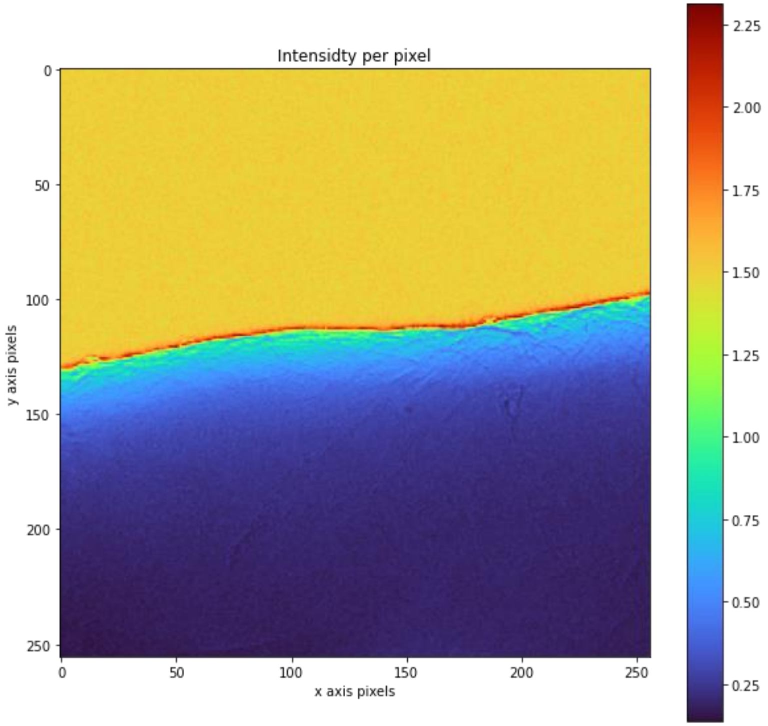
Pig Aorta



Air



Blood

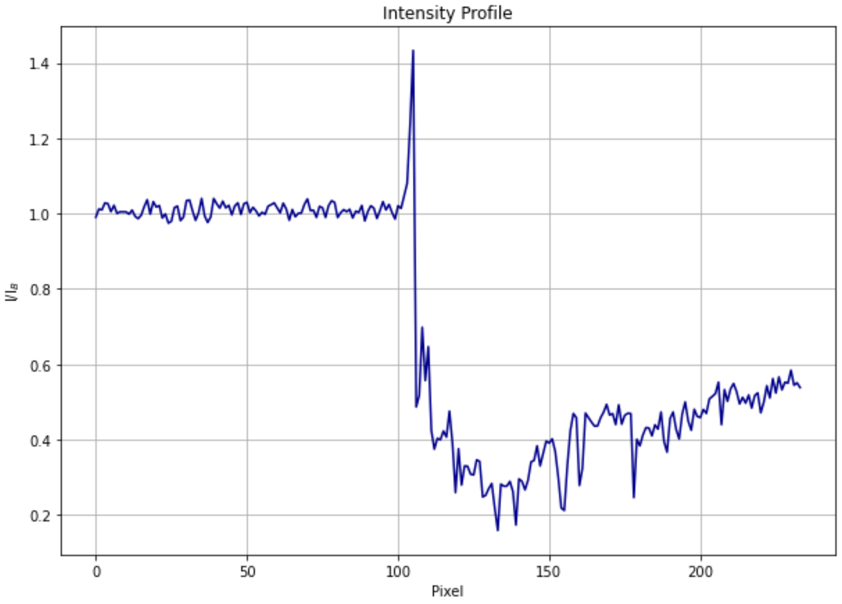


Povidone iodine

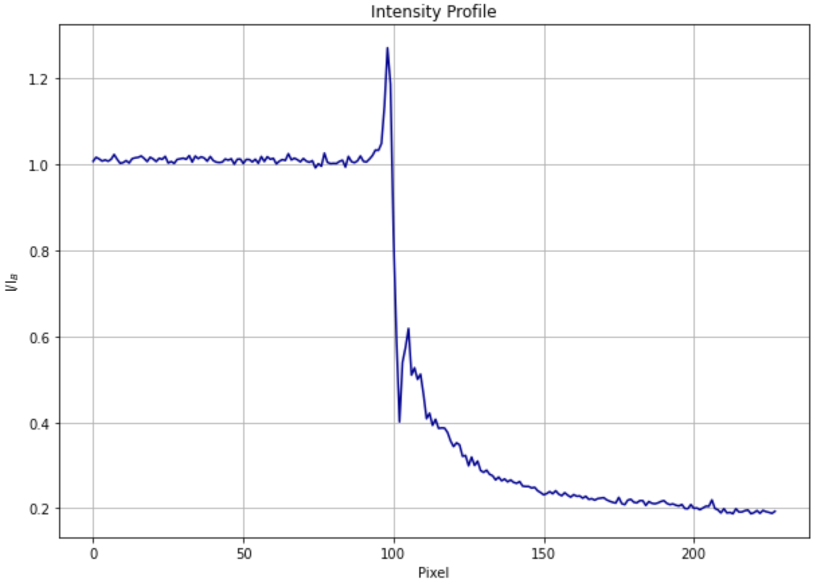
Experimental Results

Pig Aorta

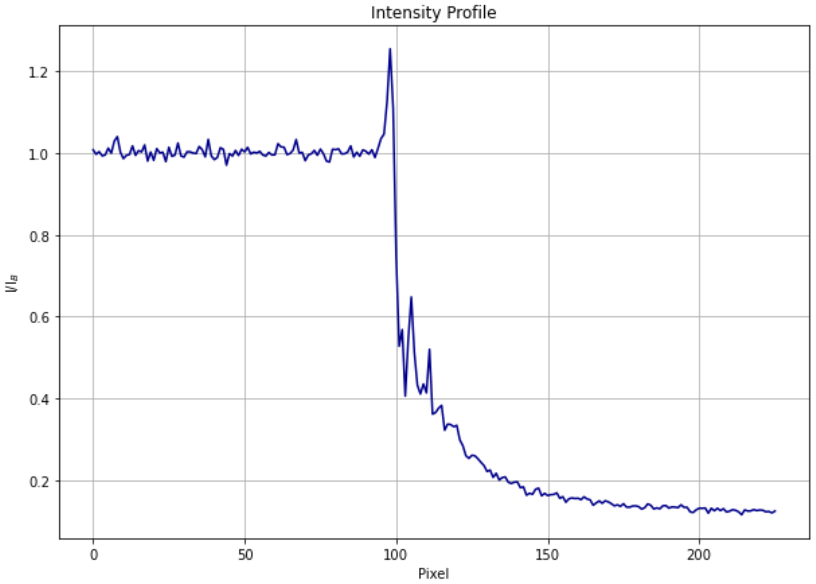
Air

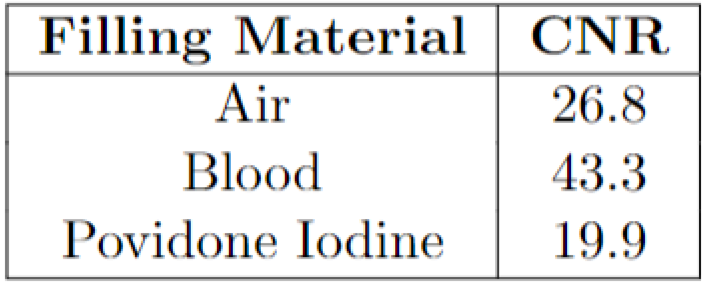


Blood



Povidone iodine

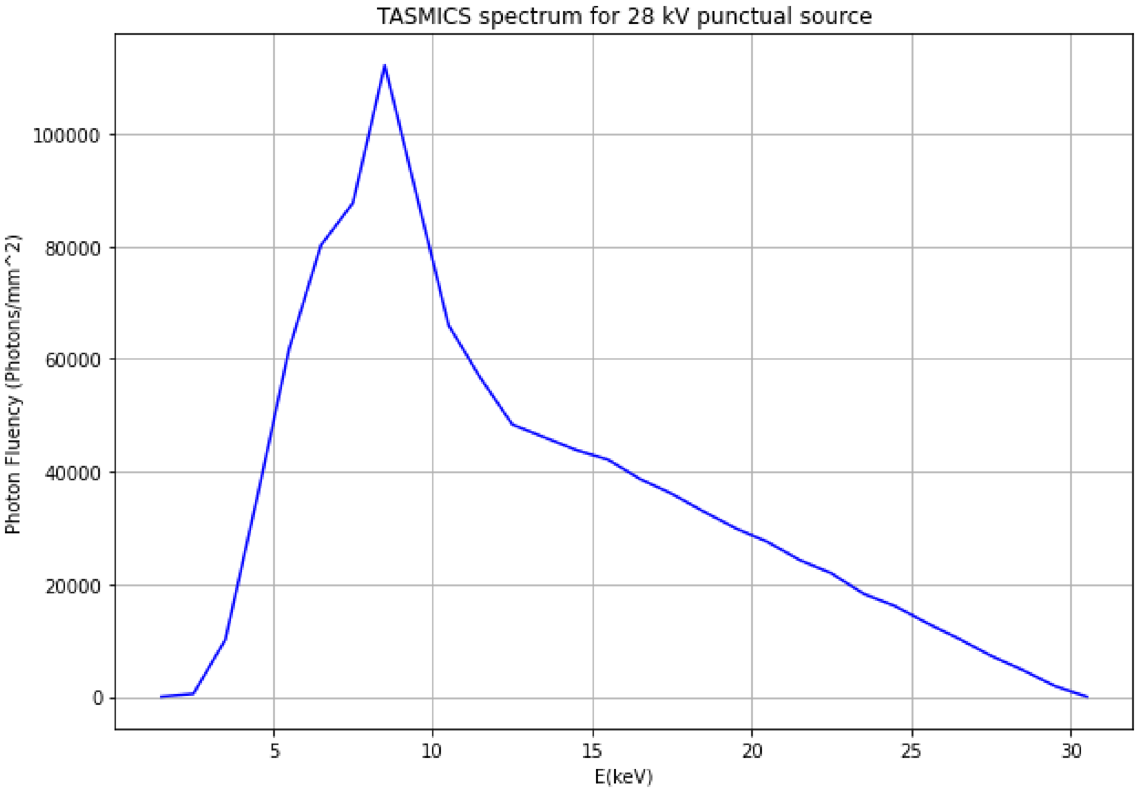




Filling Material	CNR
Air	26.8
Blood	43.3
Povidone Iodine	19.9

Computational Results

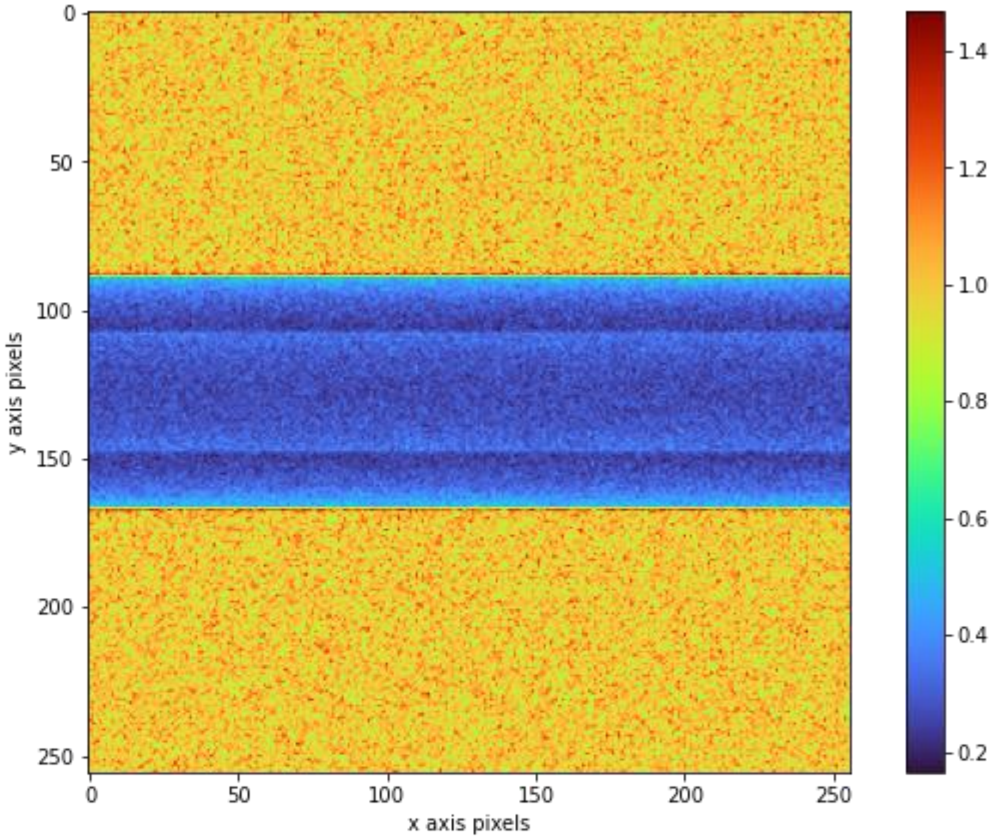
Sample: PVC tube of various external diameters, filled with blood, 60 cm from the source
Fuente: Punctual, with energetic spectrum, covers detector width
Detector: 256 x 256 pixel matrix, 55 µm sideways, 1.80 m from the sorce

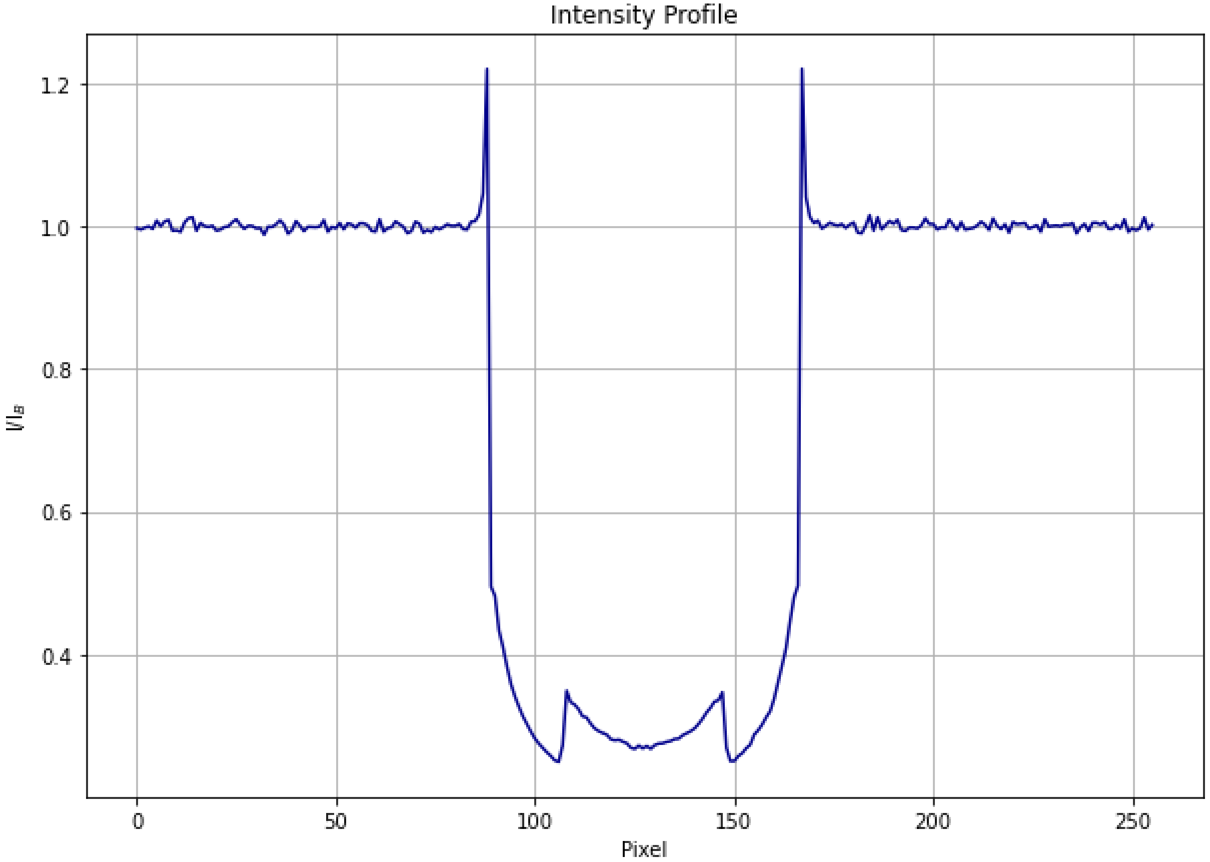


Computational Results

1.43 mm sample

10^7 photons



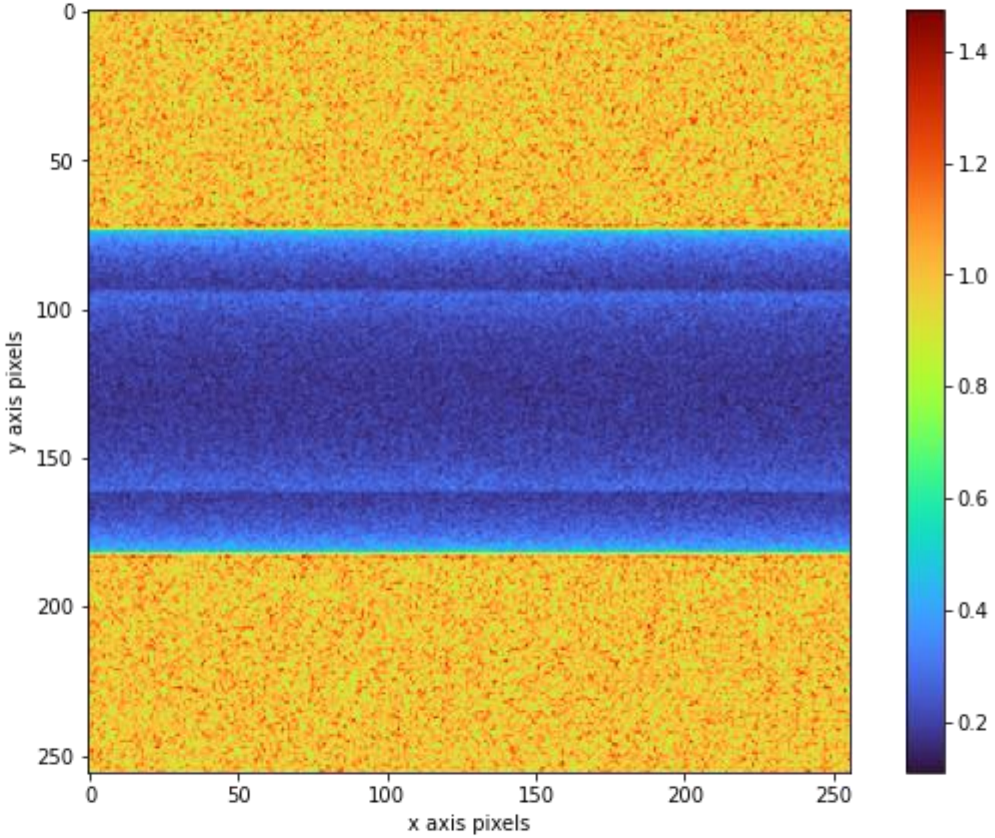


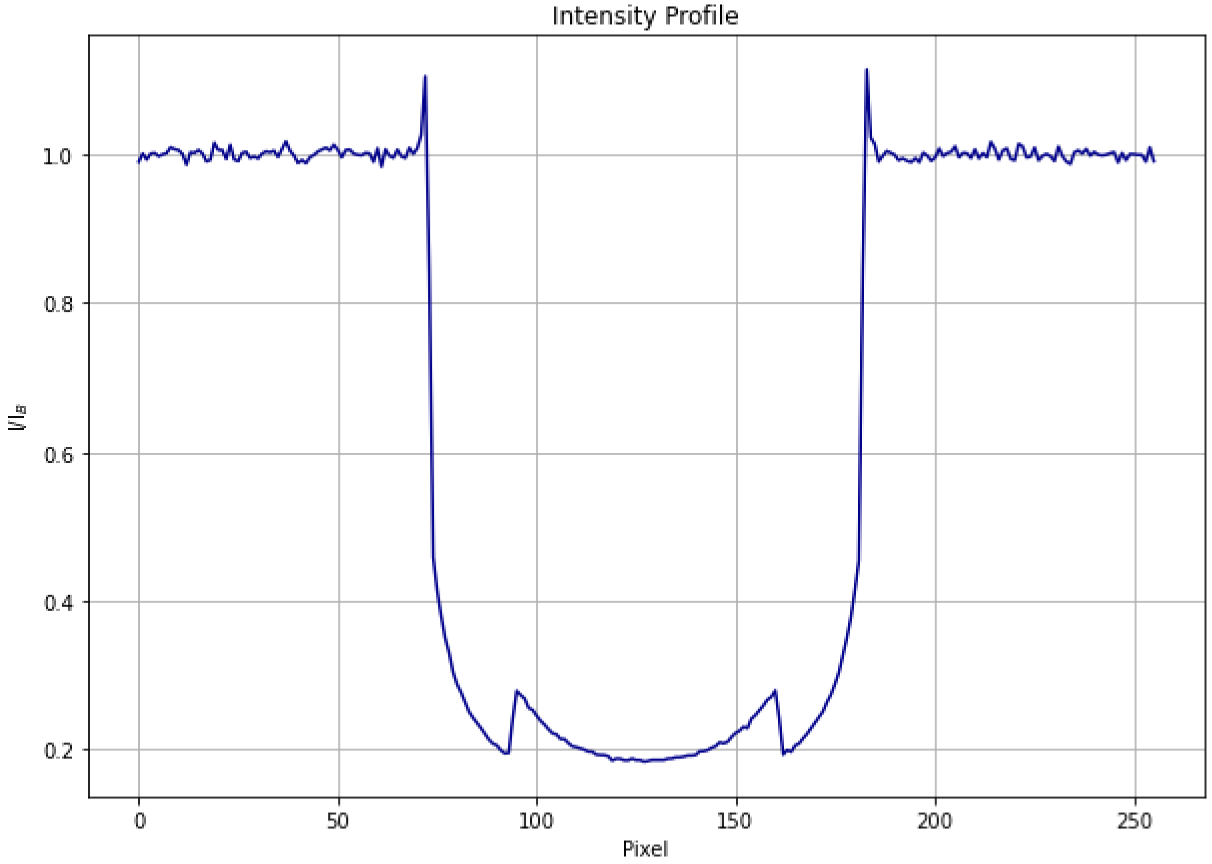
CNR = 41.1

Computational Results

2.00 mm sample

10^7 photons



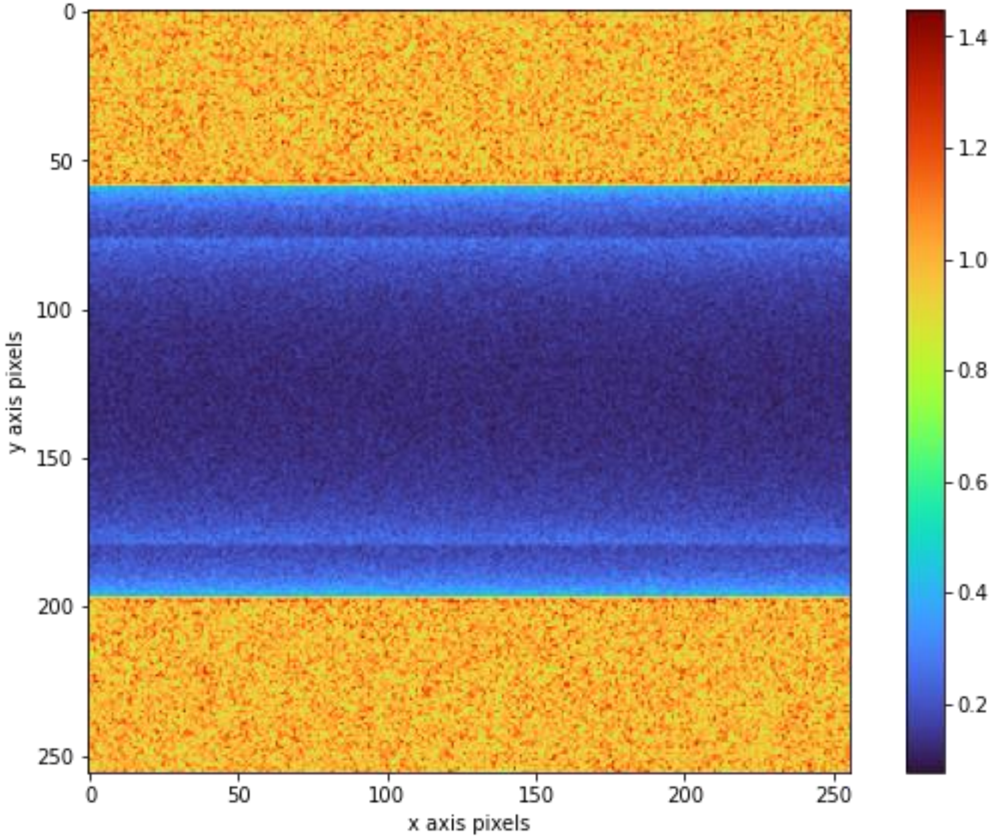


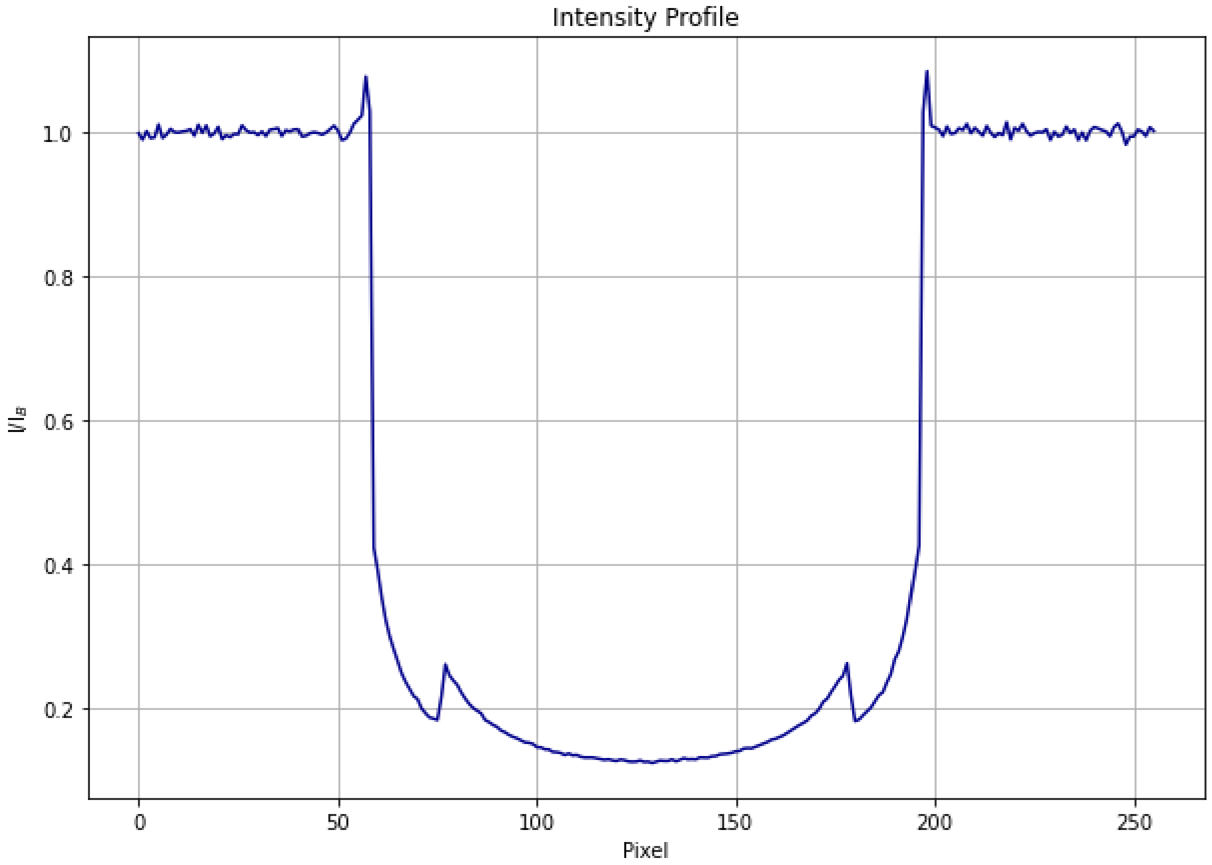
CNR = 15.9

Computational Results

2.54 mm sample

10^7 photons

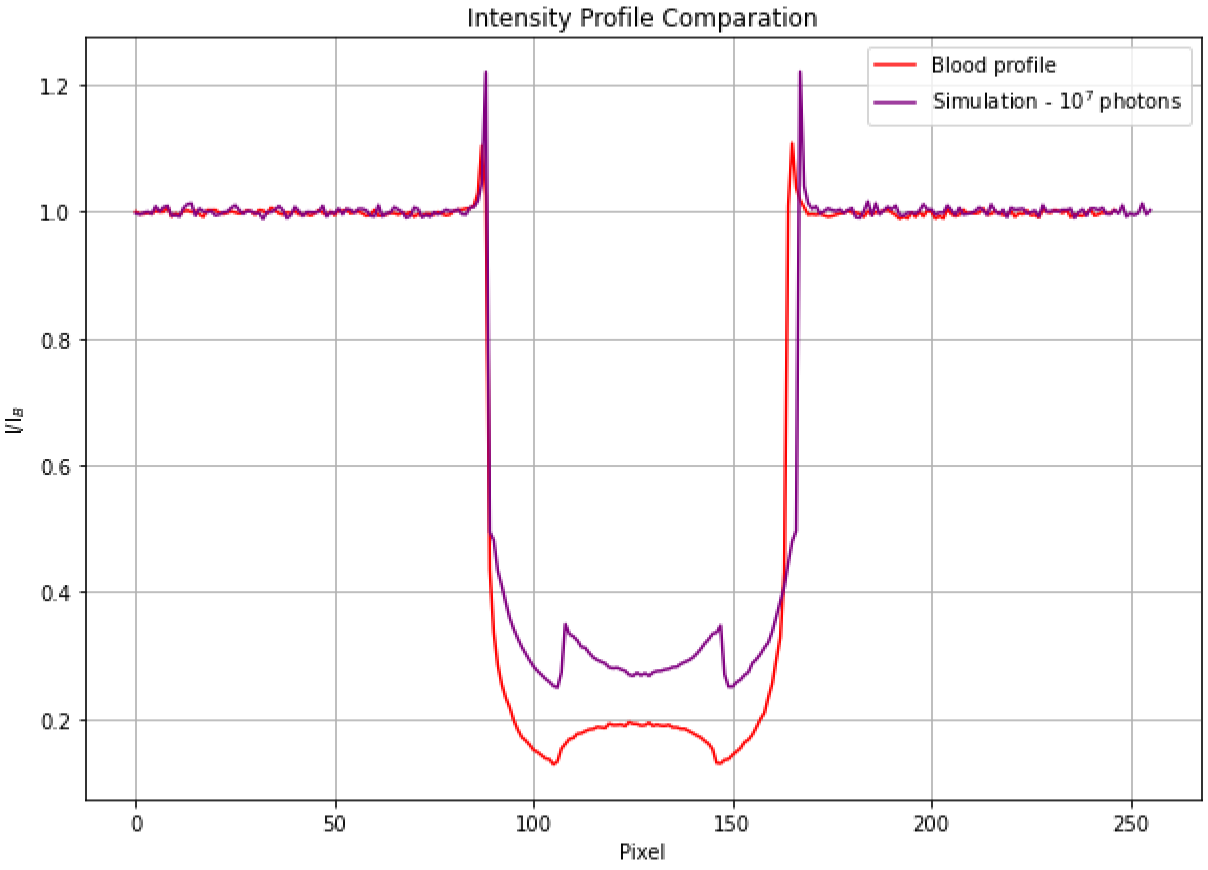




CNR = 14.6

Experimental and computational comparation

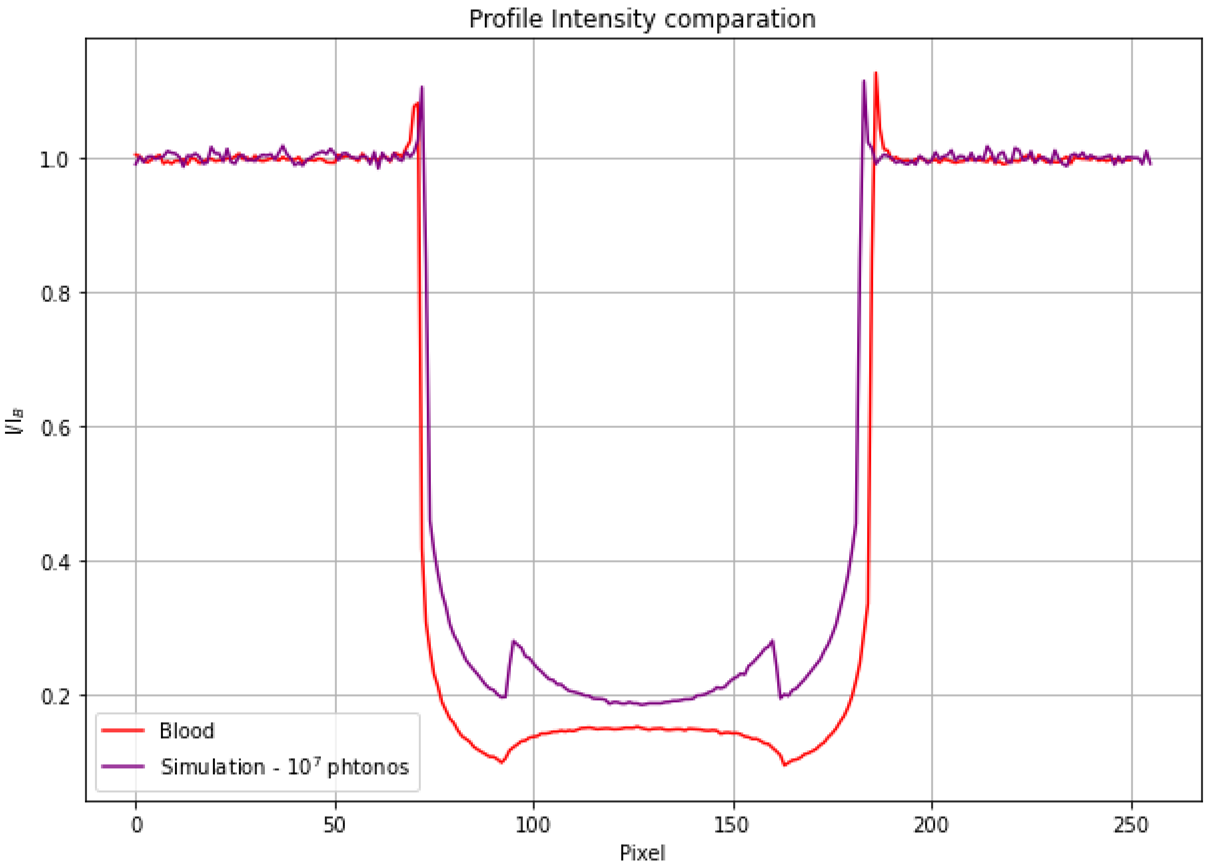
1.43 mm samples

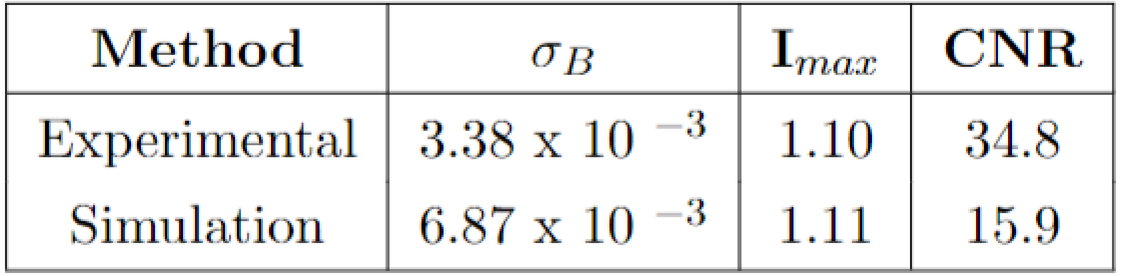


Method	σ_B	I_{max}	CNR
Experimental	3.56 x 10^{-3}	1.11	29.9
Simulation	5.34 x 10^{-3}	1.22	41.1

Experimental and computational comparation

2.00 mm samples

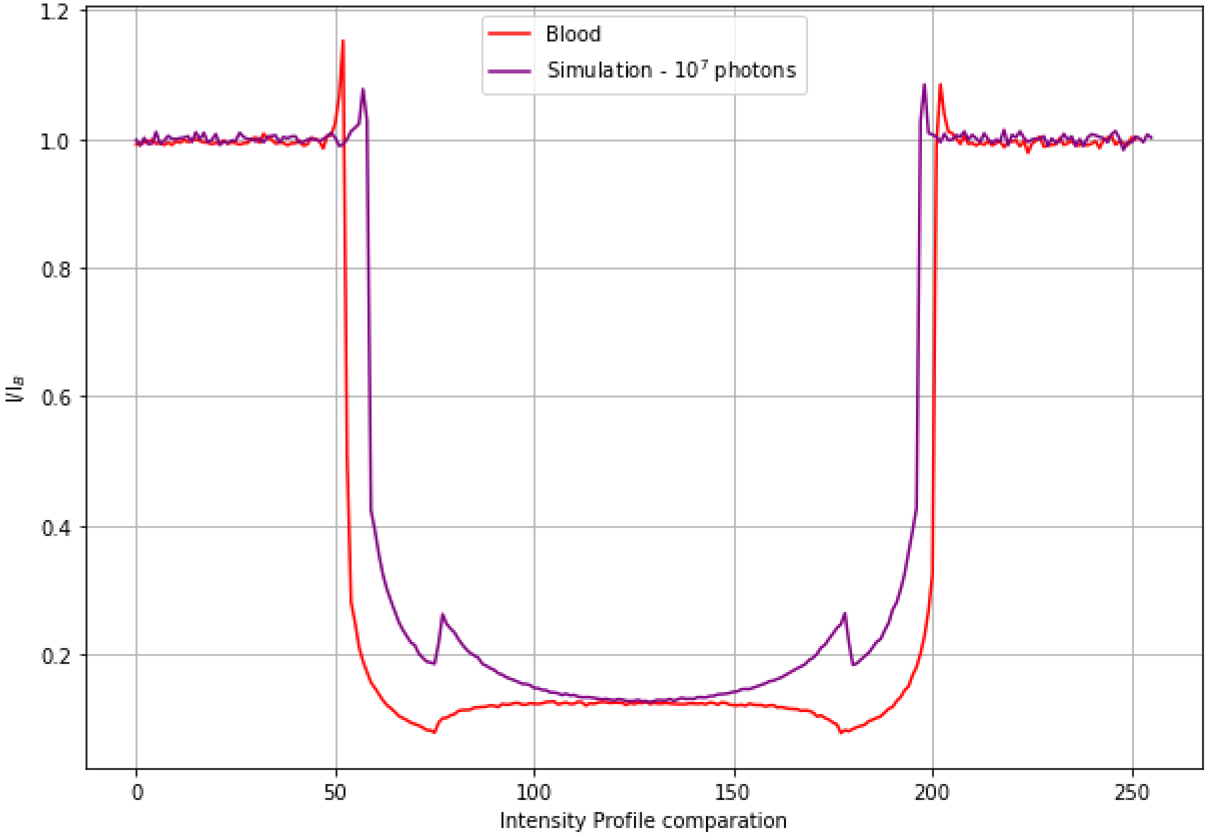


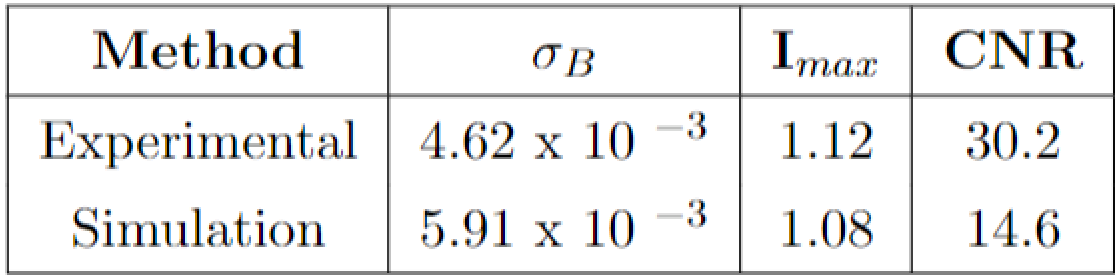


Method	σ_B	I_{max}	CNR
Experimental	3.38×10^{-3}	1.10	34.8
Simulation	6.87×10^{-3}	1.11	15.9

Experimental and computational comparation

2.54 mm samples





Method	σ_B	I_{max}	CNR
Experimental	4.62×10^{-3}	1.12	30.2
Simulation	5.91×10^{-3}	1.08	14.6

Conclusions

- An exhaustive compilation of the literature related to XPCi methods applied to various areas, including the visualization of veins and arteries, was carried out.
- A computational and laboratory study of the X-ray phase contrast imaging method could be carried out, where in both cases CNRs of the same order of magnitude were obtained.
- The phase contrast effects were visualized in the organic (pig artery) and inorganic (PVC tubes) samples analyzed in the high energy laboratory of the Universidad de los Andes.
- Simulations were carried out that reproduce the setup carried out experimentally, obtaining highly similar results.
- A user guide was developed for the McXtrace software that enables X-ray phase contrast simulations to be performed.

Bibliography

[1] F. Nüslin, "Wilhelm conrad röntgen: The scientist and his discovery," *Nuclear Inst. and Methods in Physics Research, A*, vol. 79, pp. 65–68, 2020. [Online]. Available: https://doi.org/10.1016/j.ejmp.2020.10.010

[2] H. Einarsdóttir, M. Emerson, L. Clemmensen, K. Scherer, K. Willer, M. Bech, R. Larsen, and E. Bjarne, "Novelty detection of foreign objects in food using multi-modal x-ray imaging," *Food control*, vol. 67, pp. 39–47, 2016. [Online]. Available: https://doi.org/10.1016/j.foodcont.2016.02.023

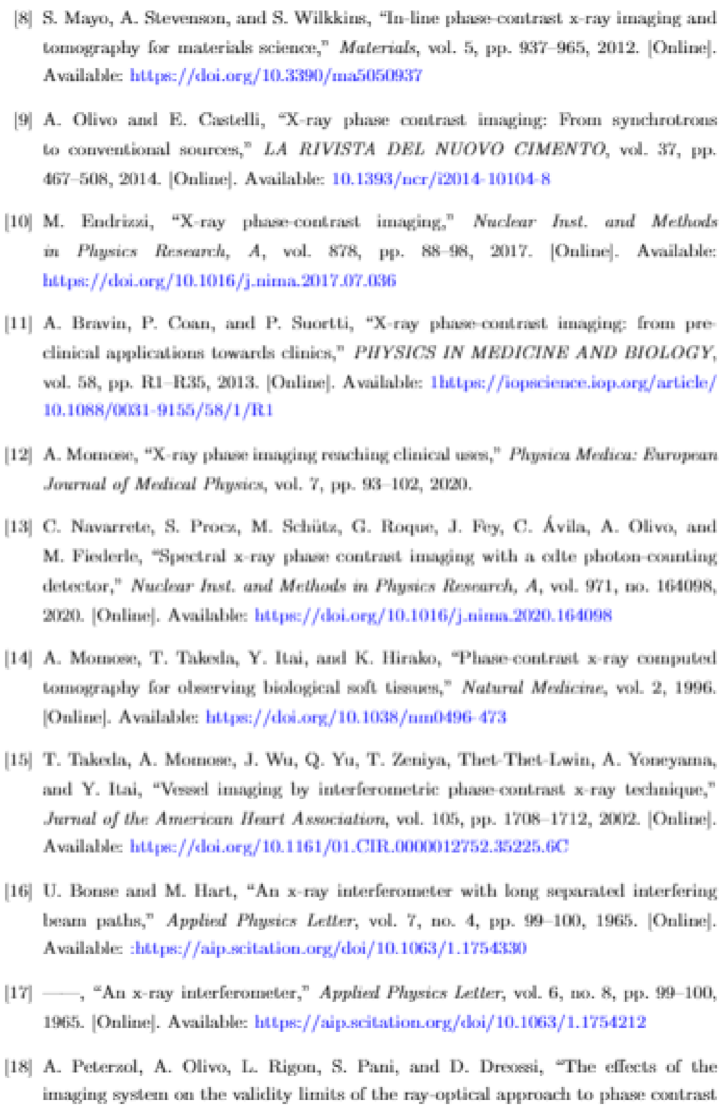
[3] P. Monnin, R. Hlushchuck, V. Djonov, R. Meuil, J. Valley, and F. Verdun, "X-ray phase contrast imaging of metallized and non-metallized biological samples," *Physics in Medicine and Biology*, vol. 16, pp. 172–178, 2006. [Online]. Available: https://doi-org.ezproxy.uniandes.edu.co:8443/10.1078/0939-3889-00312

[4] A. Momose, "Recent advances in x-ray phase imaging," *Japanese Journal of Applied Physics*, vol. 44, pp. 6355–6367, 2005. [Online]. Available: https://iopscience.iop.org/article/10.1143/JJAP.44.6355

[5] R. Lewis, "Medical phase contrast x-ray imaging: current status and future prospects," *Physics in Medicine and Biology*, vol. 49, pp. 3573–3583, 2004. [Online]. Available: https://doi.org/10.1088/0031-9155/49/16/005

[6] A. Momose, "Demonstration of phase-contrast x-ray computed tomography using an x-ray interferometer," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 352, no. 3, pp. 622–628, 1995. [Online]. Available: https://doi.org/10.1016/0168-9002(95)90017-9

[7] X. Zhang, X.-S. Liu, X.-R. Yang, C. Shao-Liang, P.-P. Zhu, and Q. Yuang, "Mouse blood vessel imaging by in-line x-ray phase-contrast imaging," *Physics in Medicine and Biology*, vol. 53, pp. 5735–5743, 2008. [Online]. Available: doi:10.1088/0031-9155/53/20/011



[8] S. Mayo, A. Stevenson, and S. Wilkkins, "In-line phase-contrast x-ray imaging and tomography for materials science," *Materials*, vol. 5, pp. 937–965, 2012. [Online]. Available: https://doi.org/10.3390/ma5050937

[9] A. Olivo and E. Castelli, "X-ray phase contrast imaging: From synchrotrons to conventional sources," *LA RIVISTA DEL NUOVO CIMENTO*, vol. 37, pp. 467–508, 2014. [Online]. Available: 10.1393/ncr/i2014-10104-8

[10] M. Endrizzi, "X-ray phase-contrast imaging," *Nuclear Inst. and Methods in Physics Research, A*, vol. 878, pp. 88–98, 2017. [Online]. Available: https://doi.org/10.1016/j.nima.2017.07.036

[11] A. Bravin, P. Coan, and P. Suortti, "X-ray phase-contrast imaging: from pre-clinical applications towards clinics," *PHYSICS IN MEDICINE AND BIOLOGY*, vol. 58, pp. R1–R35, 2013. [Online]. Available: 1https://iopscience.iop.org/article/10.1088/0031-9155/58/1/R1

[12] A. Momose, "X-ray phase imaging reaching clinical uses," *Physica Medica: European Journal of Medical Physics*, vol. 7, pp. 93–102, 2020.

[13] C. Navarrete, S. Procz, M. Schütz, G. Roque, J. Fey, C. Ávila, A. Olivo, and M. Fiederle, "Spectral x-ray phase contrast imaging with a cdte photon-counting detector," *Nuclear Inst. and Methods in Physics Research, A*, vol. 971, no. 164098, 2020. [Online]. Available: https://doi.org/10.1016/j.nima.2020.164098

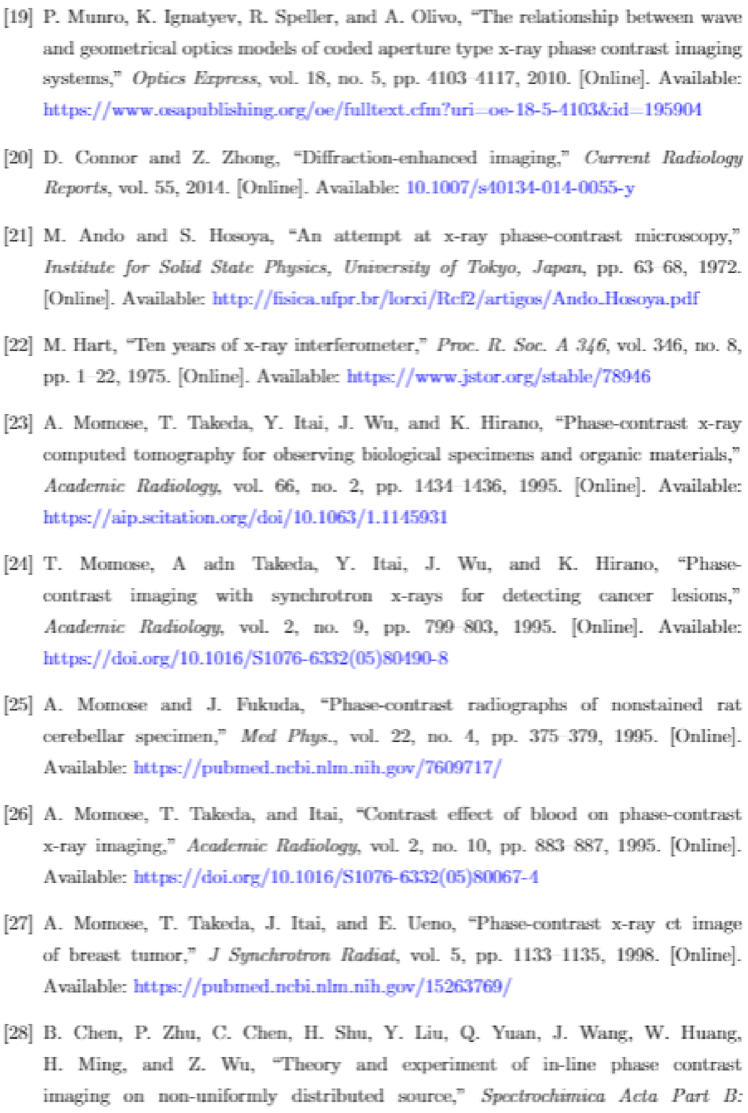
[14] A. Momose, T. Takeda, Y. Itai, and K. Hirako, "Phase-contrast x-ray computed tomography for observing biological soft tissues," *Natural Medicine*, vol. 2, 1996. [Online]. Available: https://doi.org/10.1038/nm0496-473

[15] T. Takeda, A. Momose, J. Wu, Q. Yu, T. Zeniya, Thet-Thet-Lwin, A. Yoneyama, and Y. Itai, "Vessel imaging by interferometric phase-contrast x-ray technique," *Jurnal of the American Heart Association*, vol. 105, pp. 1708–1712, 2002. [Online]. Available: https://doi.org/10.1161/01.CIR.0000012752.35225.6C

[16] U. Bonse and M. Hart, "An x-ray interferometer with long separated interfering beam paths," *Applied Physics Letter*, vol. 7, no. 4, pp. 99–100, 1965. [Online]. Available: :https://aip.scitation.org/doi/10.1063/1.1754330

[17] ——, "An x-ray interferometer," *Applied Physics Letter*, vol. 6, no. 8, pp. 99–100, 1965. [Online]. Available: https://aip.scitation.org/doi/10.1063/1.1754212

[18] A. Peterzol, A. Olivo, L. Rigon, S. Pani, and D. Dreossi, "The effects of the imaging system on the validity limits of the ray-optical approach to phase contrast



[19] P. Munro, K. Ignatyev, R. Speller, and A. Olivo, "The relationship between wave and geometrical optics models of coded aperture type x-ray phase contrast imaging systems," *Optics Express*, vol. 18, no. 5, pp. 4103–4117, 2010. [Online]. Available: https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-18-5-4103&id=195904

[20] D. Connor and Z. Zhong, "Diffraction-enhanced imaging," *Current Radiology Reports*, vol. 55, 2014. [Online]. Available: 10.1007/s40134-014-0055-y

[21] M. Ando and S. Hosoya, "An attempt at x-ray phase-contrast microscopy," *Institute for Solid State Physics, University of Tokyo, Japan*, pp. 63–68, 1972. [Online]. Available: http://fisica.ufpr.br/lorxi/Rcf2/artigos/Ando_Hosoya.pdf

[22] M. Hart, "Ten years of x-ray interferometer," *Proc. R. Soc. A 346*, vol. 346, no. 8, pp. 1–22, 1975. [Online]. Available: https://www.jstor.org/stable/78946

[23] A. Momose, T. Takeda, Y. Itai, J. Wu, and K. Hirano, "Phase-contrast x-ray computed tomography for observing biological specimens and organic materials," *Academic Radiology*, vol. 66, no. 2, pp. 1434–1436, 1995. [Online]. Available: https://aip.scitation.org/doi/10.1063/1.1145931

[24] T. Momose, A adn Takeda, Y. Itai, J. Wu, and K. Hirano, "Phase-contrast imaging with synchrotron x-rays for detecting cancer lesions," *Academic Radiology*, vol. 2, no. 9, pp. 799–803, 1995. [Online]. Available: https://doi.org/10.1016/S1076-6332(05)80490-8

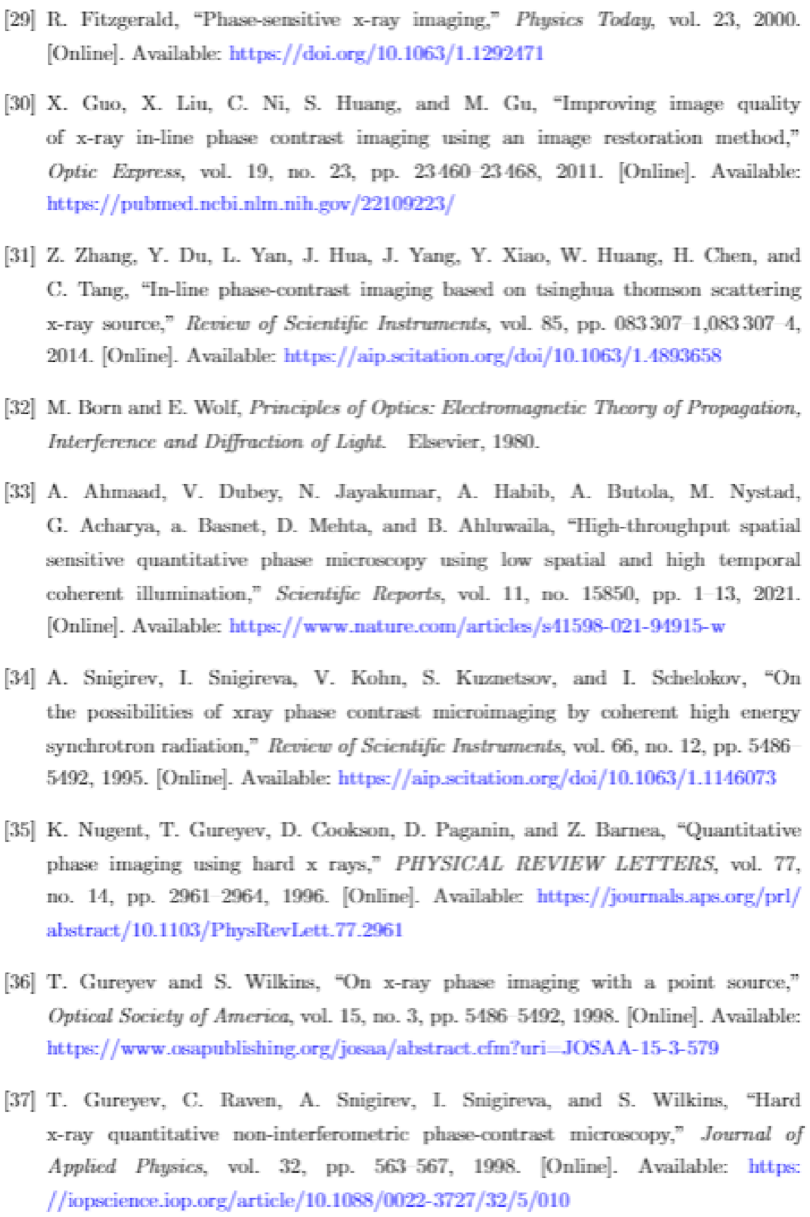
[25] A. Momose and J. Fukuda, "Phase-contrast radiographs of nonstained rat cerebellar specimen," *Med Phys.*, vol. 22, no. 4, pp. 375–379, 1995. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/7609717/

[26] A. Momose, T. Takeda, and Itai, "Contrast effect of blood on phase-contrast x-ray imaging," *Academic Radiology*, vol. 2, no. 10, pp. 883–887, 1995. [Online]. Available: https://doi.org/10.1016/S1076-6332(05)80067-4

[27] A. Momose, T. Takeda, J. Itai, and E. Ueno, "Phase-contrast x-ray ct image of breast tumor," *J Synchrotron Radiat*, vol. 5, pp. 1133–1135, 1998. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/15263769/

[28] B. Chen, P. Zhu, C. Chen, H. Shu, Y. Liu, Q. Yuan, J. Wang, W. Huang, H. Ming, and Z. Wu, "Theory and experiment of in-line phase contrast imaging on non-uniformly distributed source," *Spectrochimica Acta Part B:*

Bibliography



[29] R. Fitzgerald, "Phase-sensitive x-ray imaging," *Physics Today*, vol. 23, 2000. [Online]. Available: https://doi.org/10.1063/1.1292471

[30] X. Guo, X. Liu, C. Ni, S. Huang, and M. Gu, "Improving image quality of x-ray in-line phase contrast imaging using an image restoration method," *Optic Express*, vol. 19, no. 23, pp. 23 460–23 468, 2011. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/22109223/

[31] Z. Zhang, Y. Du, L. Yan, J. Hua, J. Yang, Y. Xiao, W. Huang, H. Chen, and C. Tang, "In-line phase-contrast imaging based on tsinghua thomson scattering x-ray source," *Review of Scientific Instruments*, vol. 85, pp. 083 307–1,083 307–4, 2014. [Online]. Available: https://aip.scitation.org/doi/10.1063/1.4893658

[32] M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*. Elsevier, 1980.

[33] A. Ahmaad, V. Dubey, N. Jayakumar, A. Habib, A. Butola, M. Nystad, G. Acharya, a. Basnet, D. Mehta, and B. Ahluwaila, "High-throughput spatial sensitive quantitative phase microscopy using low spatial and high temporal coherent illumination," *Scientific Reports*, vol. 11, no. 15850, pp. 1–13, 2021. [Online]. Available: https://www.nature.com/articles/s41598-021-94915-w

[34] A. Snigirev, I. Snigireva, V. Kohn, S. Kuznetsov, and I. Schelokov, "On the possibilities of xray phase contrast microimaging by coherent high energy synchrotron radiation," *Review of Scientific Instruments*, vol. 66, no. 12, pp. 5486–5492, 1995. [Online]. Available: https://aip.scitation.org/doi/10.1063/1.1146073

[35] K. Nugent, T. Gureyev, D. Cookson, D. Paganin, and Z. Barnea, "Quantitative phase imaging using hard x rays," *PHYSICAL REVIEW LETTERS*, vol. 77, no. 14, pp. 2961–2964, 1996. [Online]. Available: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.77.2961

[36] T. Gureyev and S. Wilkins, "On x-ray phase imaging with a point source," *Optical Society of America*, vol. 15, no. 3, pp. 5486–5492, 1998. [Online]. Available: https://www.osapublishing.org/josaa/abstract.cfm?uri=JOSAA-15-3-579

[37] T. Gureyev, C. Raven, A. Snigirev, I. Snigireva, and S. Wilkins, "Hard x-ray quantitative non-interferometric phase-contrast microscopy," *Journal of Applied Physics*, vol. 32, pp. 563–567, 1998. [Online]. Available: https://iopscience.iop.org/article/10.1088/0022-3727/32/5/010

[38] P. Cloetens, W. Ludwig, J. Barucher, D. Van Dyck, J. Van Landuyt, J. Guigay, and M. Schlenker, "Holotomography: Quantitative phase tomography with micrometer resolution using hard synchrotron radiation x rays," *Applied Physics Letters*, vol. 75, no. 19, pp. 2912–2914, 1999. [Online]. Available: http://dx.doi.org/10.1063/1.125225

[39] A. Bronnikov, "Reconstruction formulas in phase-contrast tomography," *Optics Communication*, vol. 171, pp. 239–244, 1999. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0030401899005751

[40] A. Barty, K. Nugent, A. Roberts, and D. Paganin, "Quantitative phase tomography," *Optics Communication*, vol. 175, pp. 329–336, 2000. [Online]. Available: http://xrm.phys.northwestern.edu/research/pdf_papers/2000/barty_optcomm_2000.pdf

[41] P. Bleuet, P. Cloetens, P. Gergaud, D. Mariolle, N. Chevalier, R. Tucoulou, J. Susini, and A. Chabli, "A hard x-ray nanoprobe for scanning and projection nanotomography," *Review of Scientific Instruments*, vol. 80, pp. 741–749, 2009. [Online]. Available: https://doi.org/10.1063/1.3117489

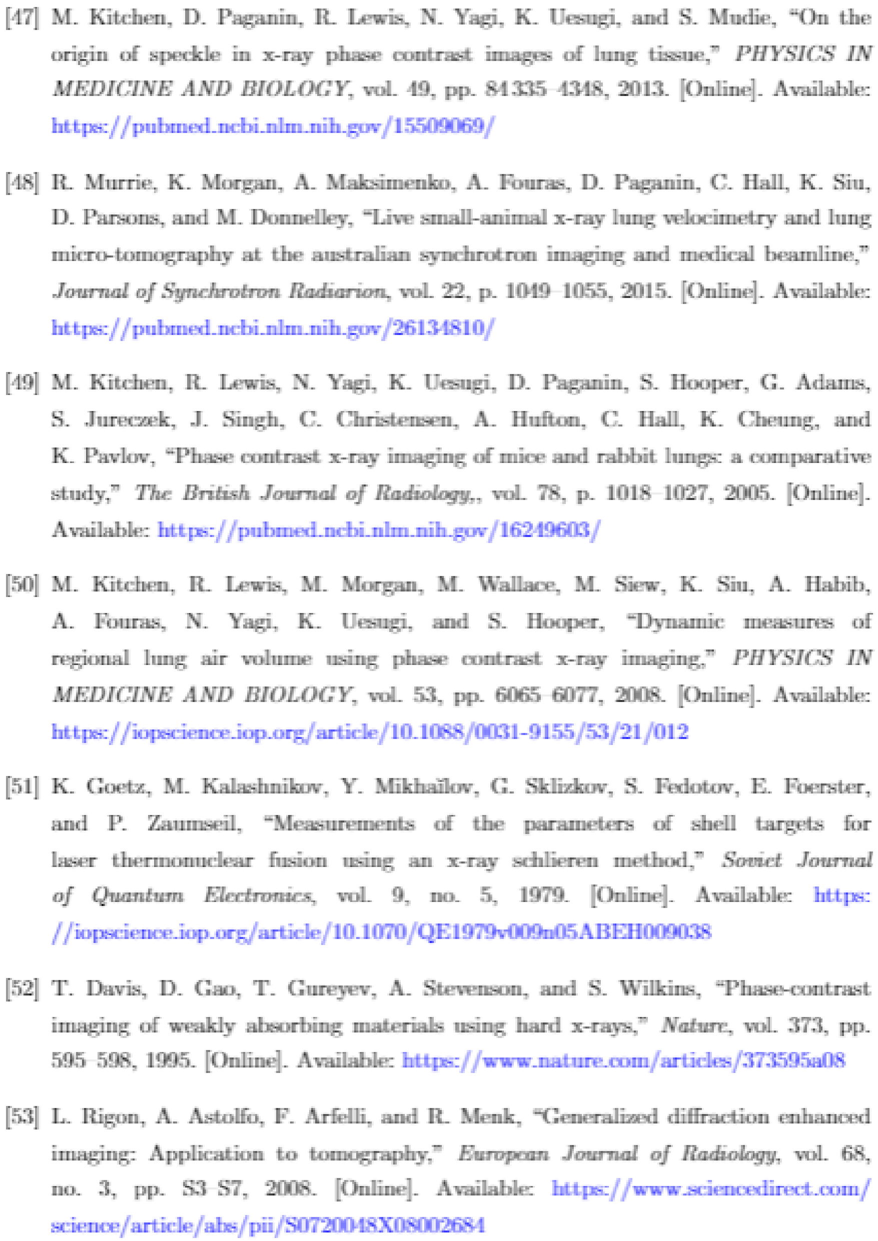
[42] P. Cloetens, J. Baruchel, M. Pateryon-Salomé, J. Bullière, and G. Peix, "Observation of microstructure and damage in materials by phase sensitive radiography and tomography," *Journal of Applied Physics*, vol. 81, no. 9, pp. 5878–5886, 1997. [Online]. Available: http://dx.doi.org/10.1063/1.364374

[43] J. Bullière, E. Marie, P. Cloetens, G. Lormand, and R. Fougères, "Characterization of internal damage in a mmcp using x-ray synchrotron phase contrast microtomography," *Acta Materiala*, vol. 47, no. 5, pp. 1613–1625, 1999. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S1359645499000245

[44] P. Spanne, C. Raven, I. Snigireva, and A. Snigirev, "In-line holography and phase-contrast microtomography with high energy x-rays," *Physics in Medicine Biology*, vol. 44, pp. 741–749, 1998. [Online]. Available: https://iopscience.iop.org/article/10.1088/0031-9155/44/3/016

[45] M. Langer, A. Pacureanu, H. Suhone, Q. Grimal, P. Cloetens, and F. Peyrin, "X-ray phase nanotomography resolves the 3d human bone ultrastructure," *PLOS ONE*, vol. 7, no. 8, pp. 1–7, 2012. [Online]. Available: https://doi.org/10.1371/journal.pone.0035691

[46] P. Varga, A. Pacureanu, M. Langer, H. Suhinen, B. Hesse, Q. Grimal, P. Cloetens, K. Raum, and F. Peyrin, "Investigation of the three-dimensional orientation of mineralized collagen fibrils in human lamellar bone using synchrotron x-ray phase



[47] M. Kitchen, D. Paganin, R. Lewis, N. Yagi, K. Uesugi, and S. Mudie, "On the origin of speckle in x-ray phase contrast images of lung tissue," *PHYSICS IN MEDICINE AND BIOLOGY*, vol. 49, pp. 84 335–4348, 2013. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/15509069/

[48] R. Murrie, K. Morgan, A. Maksimenko, A. Fouras, D. Paganin, C. Hall, K. Siu, D. Parsons, and M. Donnelley, "Live small-animal x-ray lung velocimetry and lung micro-tomography at the australian synchrotron imaging and medical beamline," *Journal of Synchrotron Radiarion*, vol. 22, p. 1049–1055, 2015. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/26134810/

[49] M. Kitchen, R. Lewis, N. Yagi, K. Uesugi, D. Paganin, S. Hooper, G. Adams, S. Jureczek, J. Singh, C. Christensen, A. Hufton, C. Hall, K. Cheung, and K. Pavlov, "Phase contrast x-ray imaging of mice and rabbit lungs: a comparative study," *The British Journal of Radiology,*, vol. 78, p. 1018–1027, 2005. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/16249603/

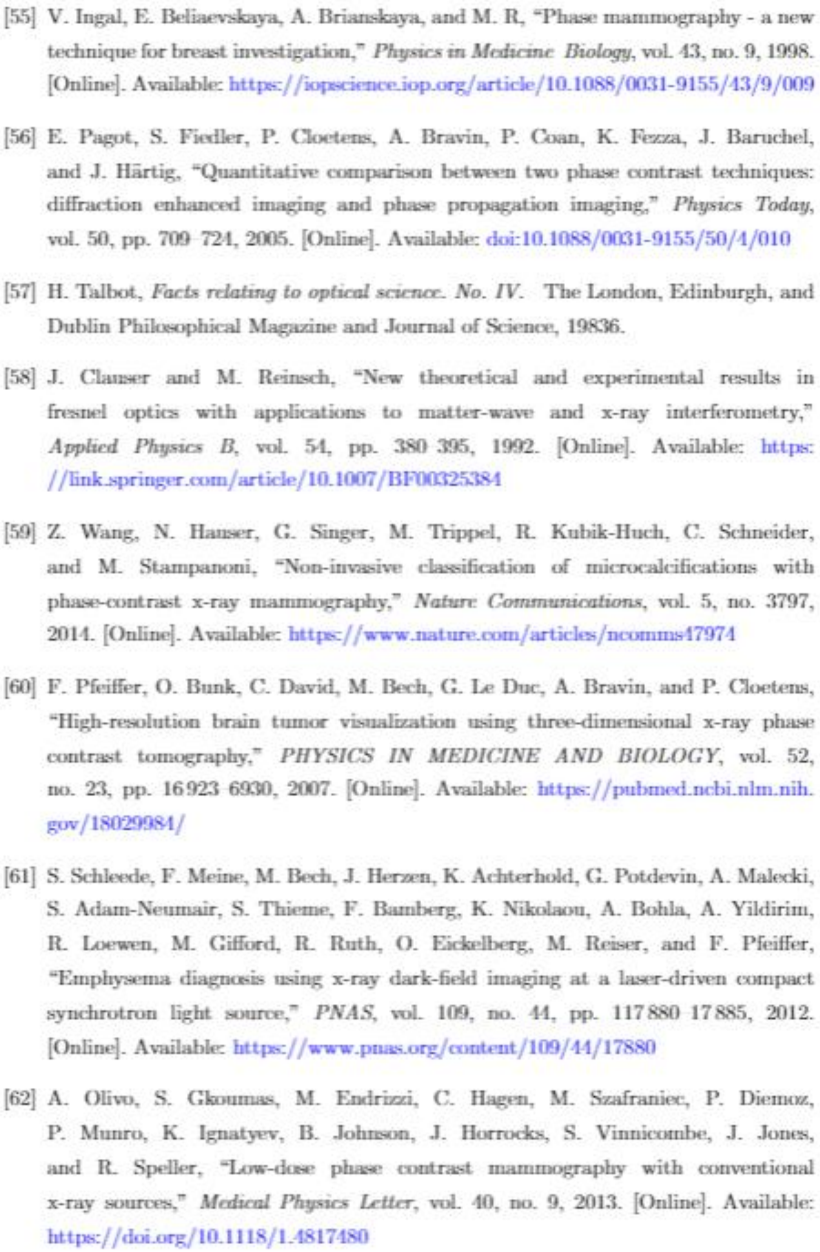
[50] M. Kitchen, R. Lewis, M. Morgan, M. Wallace, M. Siew, K. Siu, A. Habib, A. Fouras, N. Yagi, K. Uesugi, and S. Hooper, "Dynamic measures of regional lung air volume using phase contrast x-ray imaging," *PHYSICS IN MEDICINE AND BIOLOGY*, vol. 53, pp. 6065–6077, 2008. [Online]. Available: https://iopscience.iop.org/article/10.1088/0031-9155/53/21/012

[51] K. Goetz, M. Kalashnikov, Y. Mikhaĭlov, G. Sklizkov, S. Fedotov, E. Foerster, and P. Zaumseil, "Measurements of the parameters of shell targets for laser thermonuclear fusion using an x-ray schlieren method," *Soviet Journal of Quantum Electronics*, vol. 9, no. 5, 1979. [Online]. Available: https://iopscience.iop.org/article/10.1070/QE1979v009n05ABEH009038

[52] T. Davis, D. Gao, T. Gureyev, A. Stevenson, and S. Wilkins, "Phase-contrast imaging of weakly absorbing materials using hard x-rays," *Nature*, vol. 373, pp. 595–598, 1995. [Online]. Available: https://www.nature.com/articles/373595a08

[53] L. Rigon, A. Astolfo, F. Arfelli, and R. Menk, "Generalized diffraction enhanced imaging: Application to tomography," *European Journal of Radiology*, vol. 68, no. 3, pp. S3–S7, 2008. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0720048X08002684

Bibliography



[55] V. Ingal, E. Beliaevskaya, A. Brianskaya, and M. R, "Phase mammography - a new technique for breast investigation," *Physics in Medicine Biology*, vol. 43, no. 9, 1998. [Online]. Available: https://iopscience.iop.org/article/10.1088/0031-9155/43/9/009

[56] E. Pagot, S. Fiedler, P. Cloetens, A. Bravin, P. Coan, K. Fezza, J. Baruchel, and J. Härtig, "Quantitative comparison between two phase contrast techniques: diffraction enhanced imaging and phase propagation imaging," *Physics Today*, vol. 50, pp. 709–724, 2005. [Online]. Available: doi:10.1088/0031-9155/50/4/010

[57] H. Talbot, *Facts relating to optical science. No. IV.* The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 19836.

[58] J. Clauser and M. Reinsch, "New theoretical and experimental results in fresnel optics with applications to matter-wave and x-ray interferometry," *Applied Physics B*, vol. 54, pp. 380–395, 1992. [Online]. Available: https://link.springer.com/article/10.1007/BF00325384

[59] Z. Wang, N. Hauser, G. Singer, M. Trippel, R. Kubik-Huch, C. Schneider, and M. Stampanoni, "Non-invasive classification of microcalcifications with phase-contrast x-ray mammography," *Nature Communications*, vol. 5, no. 3797, 2014. [Online]. Available: https://www.nature.com/articles/ncomms47974

[60] F. Pfeiffer, O. Bunk, C. David, M. Bech, G. Le Duc, A. Bravin, and P. Cloetens, "High-resolution brain tumor visualization using three-dimensional x-ray phase contrast tomography," *PHYSICS IN MEDICINE AND BIOLOGY*, vol. 52, no. 23, pp. 16 923–6930, 2007. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/18029984/

[61] S. Schleede, F. Meine, M. Bech, J. Herzen, K. Achterhold, G. Potdevin, A. Malecki, S. Adam-Neumair, S. Thieme, F. Bamberg, K. Nikolaou, A. Bohla, A. Yildirim, R. Loewen, M. Gifford, R. Ruth, O. Eickelberg, M. Reiser, and F. Pfeiffer, "Emphysema diagnosis using x-ray dark-field imaging at a laser-driven compact synchrotron light source," *PNAS*, vol. 109, no. 44, pp. 117 880–17 885, 2012. [Online]. Available: https://www.pnas.org/content/109/44/17880

[62] A. Olivo, S. Gkoumas, M. Endrizzi, C. Hagen, M. Szafraniec, P. Diemoz, P. Munro, K. Ignatyev, B. Johnson, J. Horrocks, S. Vinnicombe, J. Jones, and R. Speller, "Low-dose phase contrast mammography with conventional x-ray sources," *Medical Physics Letter*, vol. 40, no. 9, 2013. [Online]. Available: https://doi.org/10.1118/1.4817480

[63] M. Marenzana, C. Hagen, P. Das Neves, M. Endrizzi, M. Szafraniec, T. Vincent, L. Rigon, F. Arfelli, R. Menk, and A. Olivo, "Synchrotron- and laboratory-based x-ray phase-contrast imaging for imaging mouse articular cartilage in the absence of radiopaque contrast agents," *Royal Society Publishing*, vol. 32, no. 2010, 2014. [Online]. Available: https://doi.org/10.1118/1.4817480

[64] C. Hagen, P. Maghsoudlou, G. Totonelli, P. Diemoz, M. Endrizzi, L. Rigon, R. Menk, F. Arfelli, D. Dreossi, E. Brun, P. Coan, A. Bravin, P. De Coppi, and A. Olivo, "High contrast microstructural visualization of natural acellular matrices by means of phase-based x-ray tomography," *Scientific Reports*, vol. 5, no. 18156, 2015. [Online]. Available: https://www.nature.com/articles/srep18156

[65] P. Modregger, T. Cremona, C. Benarafa, J. Schittny, A. Olivo, and M. Endrizzi, "Small angle x-ray scattering with edge-illumination," *Scientific Reports*, vol. 6, no. 30940, 2016. [Online]. Available: https://www.nature.com/articles/srep30940

[66] H. Wen, E. Bennet, M. Hegedus, and S. Rapacchi, "Fourier x-ray scattering radiography yields bone structural information," *Radiology*, vol. 251, no. 3, pp. 910–918, 2009. [Online]. Available: https://pubs.rsna.org/doi/pdf/10.1148/radiol.2521081903

[67] K. Morgan, M. Donnelley, D. Paganin, A. Fouras, N. Yagi, Y. Suzuki, A. Takeuchi, K. Uesugi, R. Boucher, D. Parsons, and K. Siu, "Measuring airway surface liquid depth in ex vivo mouse airways by x-ray imaging for the assessment of cystic fibrosis airway therapies," *Plos ONE*, vol. 8, no. 1, pp. 1–6, 2013. [Online]. Available: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0055822

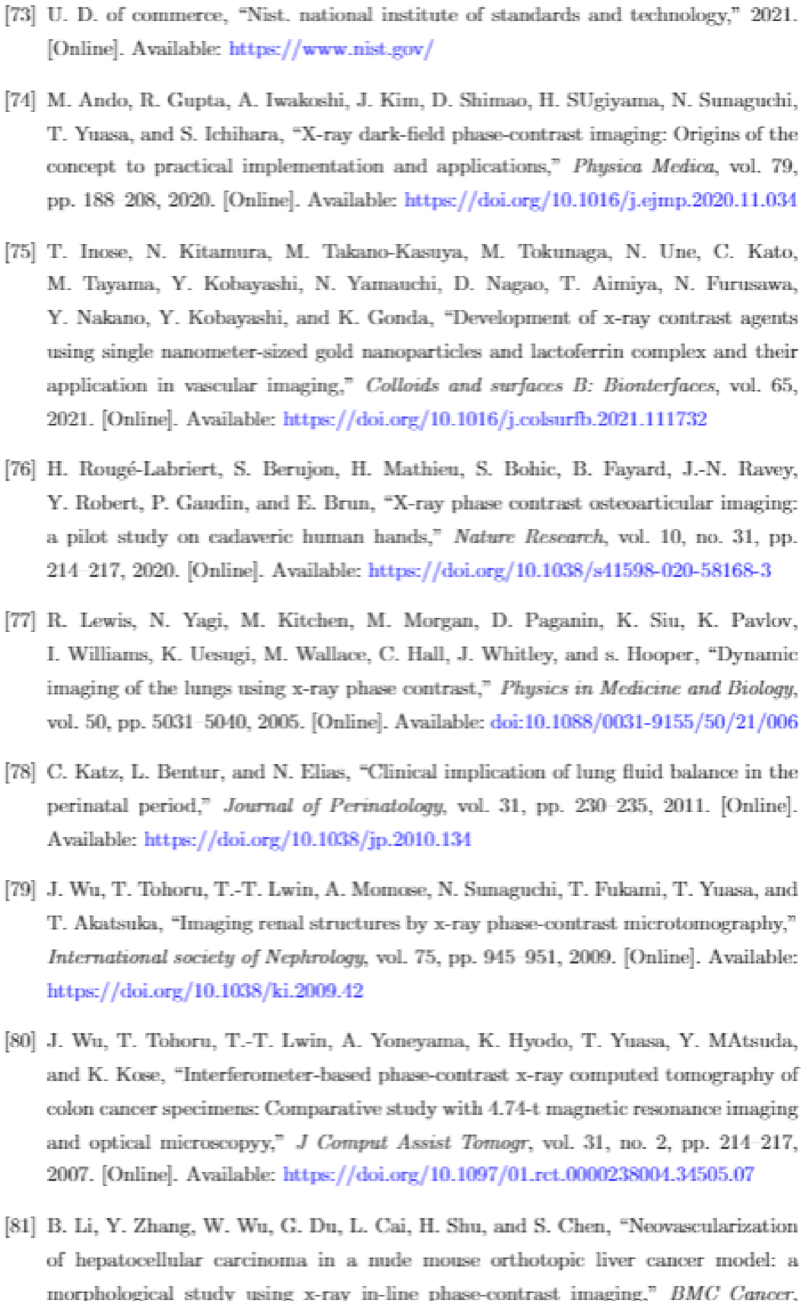
[68] ——, "At-wavelength metrology of hard x-ray mirror using near field speckle," *OSA*, vol. 22, no. 6, 2014. [Online]. Available: https://doi.org/10.1364/OE.22.006438

[69] E. Knudsen, A. Prodi, J. Baltser, M. Thomsen, P. Willendrup, M. Sanchez, C. Ferrero, E. Farhi, K. Haldrup, and A. Vickery, "Mcxtrace-an x-ray-trace simulation package," 2013. [Online]. Available: http://www.mcxtrace.org/

[70] M. Langer, Z. Cen, S. Rit, and J. M. Létang, "Towards monte carlo simulation of x-ray phase contrast using gate," *Optic Express*, vol. 28, no. 11, 2020. [Online]. Available: https://doi.org/10.1364/OE.391471

[71] E. Knudsen, P. Willendrup, E. Farhi, and S. Lefmann, K Schdmit, *User and Programmers' Guide to the X Ray-Tracing Package McXtrace, version 1.5.* 2800 Kongers Lyngby, Denmark: Technical University of Denmark, 2019.

[72] C. Pellegrini, "The development of xfels," *Nature Reviews Physics*, vol. 2, pp. 330–331, 2020. [Online]. Available: https://www.nature.com/articles/s42254-020-0197-1



[73] U. D. of commerce, "Nist. national institute of standards and technology," 2021. [Online]. Available: https://www.nist.gov/

[74] M. Ando, R. Gupta, A. Iwakoshi, J. Kim, D. Shimao, H. SUgiyama, N. Sunaguchi, T. Yuasa, and S. Ichihara, "X-ray dark-field phase-contrast imaging: Origins of the concept to practical implementation and applications," *Physica Medica*, vol. 79, pp. 188–208, 2020. [Online]. Available: https://doi.org/10.1016/j.ejmp.2020.11.034

[75] T. Inose, N. Kitamura, M. Takano-Kasuya, M. Tokunaga, N. Une, C. Kato, M. Tayama, Y. Kobayashi, N. Yamauchi, D. Nagao, T. Aimiya, N. Furusawa, Y. Nakano, Y. Kobayashi, and K. Gonda, "Development of x-ray contrast agents using single nanometer-sized gold nanoparticles and lactoferrin complex and their application in vascular imaging," *Colloids and surfaces B: Bionterfaces*, vol. 65, 2021. [Online]. Available: https://doi.org/10.1016/j.colsurfb.2021.111732

[76] H. Rougé-Labriert, S. Berujon, H. Mathieu, S. Bohic, B. Fayard, J.-N. Ravey, Y. Robert, P. Gaudin, and E. Brun, "X-ray phase contrast osteoarticular imaging: a pilot study on cadaveric human hands," *Nature Research*, vol. 10, no. 31, pp. 214–217, 2020. [Online]. Available: https://doi.org/10.1038/s41598-020-58168-3

[77] R. Lewis, N. Yagi, M. Kitchen, M. Morgan, D. Paganin, K. Siu, K. Pavlov, I. Williams, K. Uesugi, M. Wallace, C. Hall, J. Whitley, and s. Hooper, "Dynamic imaging of the lungs using x-ray phase contrast," *Physics in Medicine and Biology*, vol. 50, pp. 5031–5040, 2005. [Online]. Available: doi:10.1088/0031-9155/50/21/006

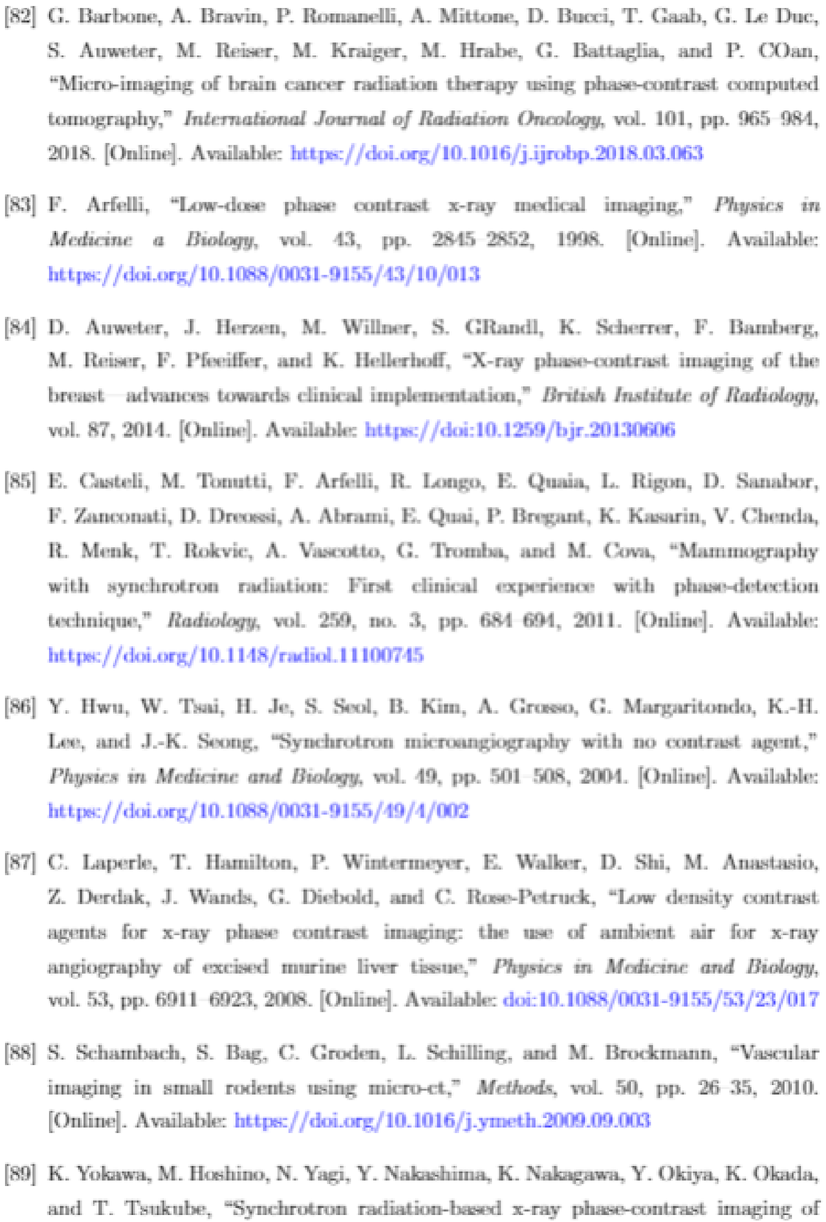
[78] C. Katz, L. Bentur, and N. Elias, "Clinical implication of lung fluid balance in the perinatal period," *Journal of Perinatology*, vol. 31, pp. 230–235, 2011. [Online]. Available: https://doi.org/10.1038/jp.2010.134

[79] J. Wu, T. Tohoru, T.-T. Lwin, A. Momose, N. Sunaguchi, T. Fukami, T. Yuasa, and T. Akatsuka, "Imaging renal structures by x-ray phase-contrast microtomography," *International society of Nephrology*, vol. 75, pp. 945–951, 2009. [Online]. Available: https://doi.org/10.1038/ki.2009.42

[80] J. Wu, T. Tohoru, T.-T. Lwin, A. Yoneyama, K. Hyodo, T. Yuasa, Y. MAtsuda, and K. Kose, "Interferometer-based phase-contrast x-ray computed tomography of colon cancer specimens: Comparative study with 4.74-t magnetic resonance imaging and optical microscopyy," *J Comput Assist Tomogr*, vol. 31, no. 2, pp. 214–217, 2007. [Online]. Available: https://doi.org/10.1097/01.rct.0000238004.34505.07

[81] B. Li, Y. Zhang, W. Wu, G. Du, L. Cai, H. Shu, and S. Chen, "Neovascularization of hepatocellular carcinoma in a nude mouse orthotopic liver cancer model: a morphological study using x-ray in-line phase-contrast imaging," *BMC Cancer*,

Bibliography



[82] G. Barbone, A. Bravin, P. Romanelli, A. Mittone, D. Bucci, T. Gaab, G. Le Duc, S. Auweter, M. Reiser, M. Kraiger, M. Hrabe, G. Battaglia, and P. COan, "Micro-imaging of brain cancer radiation therapy using phase-contrast computed tomography," *International Journal of Radiation Oncology*, vol. 101, pp. 965–984, 2018. [Online]. Available: https://doi.org/10.1016/j.ijrobp.2018.03.063

[83] F. Arfelli, "Low-dose phase contrast x-ray medical imaging," *Physics in Medicine a Biology*, vol. 43, pp. 2845–2852, 1998. [Online]. Available: https://doi.org/10.1088/0031-9155/43/10/013

[84] D. Auweter, J. Herzen, M. Willner, S. GRandl, K. Scherrer, F. Bamberg, M. Reiser, F. Pfeeiffer, and K. Hellerhoff, "X-ray phase-contrast imaging of the breast—advances towards clinical implementation," *British Institute of Radiology*, vol. 87, 2014. [Online]. Available: https://doi:10.1259/bjr.20130606

[85] E. Casteli, M. Tonutti, F. Arfelli, R. Longo, E. Quaia, L. Rigon, D. Sanabor, F. Zanconati, D. Dreossi, A. Abrami, E. Quai, P. Bregant, K. Kasarin, V. Chenda, R. Menk, T. Rokvic, A. Vascotto, G. Tromba, and M. Cova, "Mammography with synchrotron radiation: First clinical experience with phase-detection technique," *Radiology*, vol. 259, no. 3, pp. 684–694, 2011. [Online]. Available: https://doi.org/10.1148/radiol.11100745

[86] Y. Hwu, W. Tsai, H. Je, S. Seol, B. Kim, A. Grosso, G. Margaritondo, K.-H. Lee, and J.-K. Seong, "Synchrotron microangiography with no contrast agent," *Physics in Medicine and Biology*, vol. 49, pp. 501–508, 2004. [Online]. Available: https://doi.org/10.1088/0031-9155/49/4/002

[87] C. Laperle, T. Hamilton, P. Wintermeyer, E. Walker, D. Shi, M. Anastasio, Z. Derdak, J. Wands, G. Diebold, and C. Rose-Petruck, "Low density contrast agents for x-ray phase contrast imaging: the use of ambient air for x-ray angiography of excised murine liver tissue," *Physics in Medicine and Biology*, vol. 53, pp. 6911–6923, 2008. [Online]. Available: doi:10.1088/0031-9155/53/23/017

[88] S. Schambach, S. Bag, C. Groden, L. Schilling, and M. Brockmann, "Vascular imaging in small rodents using micro-ct," *Methods*, vol. 50, pp. 26–35, 2010. [Online]. Available: https://doi.org/10.1016/j.ymeth.2009.09.003

[89] K. Yokawa, M. Hoshino, N. Yagi, Y. Nakashima, K. Nakagawa, Y. Okiya, K. Okada, and T. Tsukube, "Synchrotron radiation-based x-ray phase-contrast imaging of

[90] U. Lundström, D. Larsson, A. Burvall, P. Takman, L. Scott, H. Brismar, and H. Hertz, "X-ray phase contrast for co2 microangiography," *Physics in Medicine and Biology*, vol. 57, pp. 2603–2617, 2012. [Online]. Available: doi:10.1088/0031-9155/57/9/2603

[91] C. Kang, S. Kim, H. Lee, C. Park, Y.-B. Kim, and Z.-H. Cho, "Functional mr angiography using phase contrast imaging technique at 3t mri," *NeuroImage*, vol. 50, pp. 1036–1043, 2010. [Online]. Available: https://doi.org/10.1016/j.neuroimage.2010.01.038

[92] A. Klepaczko, P. Szczypiński, M. Strzelecki, and L. Stefańczyk, "Simulation of phase contrast angiography for renal arterial models," *BioMedical Engineering OnLine*, vol. 10, pp. 17–41, 2018. [Online]. Available: https://doi.org/10.1186/s12938-018-0471-y

[93] "Elastic properties of blood vessels," *Medical Physiology*, vol. 3. [Online]. Available: https://doctorlib.info/physiology/medical/104.html