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Issue Highlights

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Clinical Evaluation of Advanced Algorithms for CCTA: A Focus on High BMI and Elevated Heart Rate Populations

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Abstract

The study aims to rigorously evaluate the performance of three advanced algorithms: Auto ALARA, CardioXPhase and CardioCapture, in enhancing the image quality and diagnostic accuracy of Coronary Computed Tomography Angiography (CCTA) in patients with high Body Mass Index (BMI) and elevated heart rates (HR). Eight patients characterized by high BMI (>30 kg/m^2) and HR (>75 bpm) were included in this retrospective study. The clarity and diagnostic quality of the images were analyzed by two experienced cardiologists using a segment-centric approach. Results showed that auto ALARA could optimize the radiation to subjects with large BMI, achieving good diagnostic image quality comparable to those with low BMI. Post-CardioXPhase, 88% (106 out of 120 segments) had diagnostic quality (average score 3.1 ± 0.37). After applying CardioCapture, all segments reached diagnostic quality with an average score of 3.6 ± 0.28. In conclusion, employing advanced algorithms, auto ALARA, CardioXPhase and CardioCapture significantly enhance diagnostic quality in CCTA images, especially for challenging patients with high BMIs and elevated heart rates.

1. Introduction

Coronary Computed Tomography Angiography (CCTA) has been established as an invaluable non-invasive diagnostic technique for the assessment of coronary artery disease (CAD). It empowers clinicians to procure intricate anatomical data without resorting to invasive measures, revolutionizing the diagnostic landscape [1]. Subsequent technological advancements in the field of CCTA have markedly enhanced both image quality and diagnostic precision, cementing its role as an indispensable instrument for evaluating patients with suspected or diagnosed CAD.

Despite these advancements, CCTA presents challenges when imaging patients with elevated Body Mass Index (BMI) and high heart rate (HR). High BMI can potentially lead to increased image noise, reduced spatial resolution, and diminished contrast-to-noise ratio, compromising the diagnostic efficacy of CCTA in this population. Additionally, patients with high HR present motion artifacts, blurring, and incomplete vessel opacification, further complicating accurate diagnosis.

To address these challenges inherent in imaging patients with elevated BMI and high HR, many technological innovations have been introduced. For instance, Electrocardiogram (ECG) triggering technology facilitates the synchronization of CT scans with a patient's cardiac cycle [2]. This capability significantly enhances the acquisition of high-quality images, even in instances of elevated heart rates. Similarly, wide-detector technology expedites scanning speed, thereby ameliorating the presence of motion artifacts and consequently improving overall image quality for patients with high HR [3].

Further technological advancements extend to algorithms designed to modulate radiation doses. These sophisticated algorithms are specifically calibrated to maintain a balance between achieving optimal image quality and minimizing radiation exposure, making them particularly beneficial for patients with high BMI. Among the more recent innovations is the introduction of a cutting-edge 320-row scanner with a rapid rotation time of 0.25 seconds (temporal resolution of 125 ms) [4]. This advanced scanner is equipped with an AI-driven dose-modulation algorithm called auto ALARA that automatically customizes the radiation dose, ensuring the least amount of radiation exposure while still preserving image integrity. CardioXphase empowers automatic selection of optimal reconstruction phase within a cardiac cycle, significantly streamlining tasks for technicians. Additionally, an AI-assisted motion correction algorithm called CardioCapture enhances correction quality and computational efficiency. This algorithm is designed to be activated whenever residual motion artifacts are detected, thereby ensuring optimal image quality. Given these technological advancements, we hypothesized that the complexity inherent in the CCTA scanning workflow could be significantly streamlined. However, it's important to note that the performance of these innovations, particularly in populations with high BMI and elevated HR, has yet to be comprehensively evaluated.

This paper aims to conduct a rigorous evaluation of this wide-detector facility and its affiliated cutting-edge algorithms, specifically their impact on image quality, diagnostic accuracy, and clinical utility in high BMI and high HR patient cohorts undergoing CCTA.

2. Materials and Methods

2.1 Data Acquisition

This investigation is a retrospective cohort study conducted over a period spanning from September 2022 to January 2023. During this timeframe, a cohort of 135 subjects underwent CCTA examination. A subset of 96 subjects, characterized by a heart rate of less than 75 beats per minute (bpm), were systematically excluded from further analysis. Of the remaining 39 subjects, eight individuals were identified with a BMI exceeding 30. Within this subgroup, the mean BMI was 36.325 kg/m^2, and the average heart rate was 83.25 bpm. Gender distribution revealed that six out of the eight subjects were male. The mean age for this specific cohort was 58 years. Comprehensive demographic and clinical characteristics of the participant population are elaborated in Table 1.

All imaging procedures were conducted using the cutting-edge 320-row detector CT scanner (uCT® ATLAS, United Imaging Healthcare), integrated with prospective ECG triggering capable of capturing data within a single cardiac cycle. The data acquisition was intricately synchronized using a bolus-tracking technique, initiated precisely 6.0 seconds after the moment the attenuation values in the descending aorta surpassed 110 Hounsfield units. The acquisition window spanned from 30% to 55% of the R-R interval or 60% to 85% of the R-R interval which will be automatically determined by the scanner. During the CCTA, the scanning parameters were customized based on individual patient anatomy and needs. The z-coverage was selected from a range of 12 cm, 14 cm, or 16 cm, contingent on the patient's heart size. The reconstruction matrix was standardized at 512 × 512 pixels, with a voxel size of 0.5 mm. The gantry rotation time was set at an ultra-fast 0.25 seconds.

Table 1: Properties of subjects included in the study.

No.	Age	Sex	BMI (Kg/m^2)	Height (feet)	Weight (lb)	Heart Rate (bpm)
1	065Y	M	43.3	5'9"	293	79
2	057Y	F	38.7	5'7"	247	81
3	071Y	M	38.7	5'6"	240	81
4	062Y	M	36.5	5'8"	240	82
5	047Y	M	35.3	7'2"	260	108
6	050Y	M	34.2	5'	175	77
7	053Y	M	33.5	5'8"	220	78
8	056Y	F	30.4	5'2"	166	80

2.2 Advanced Algorithms

2.2.1 Auto ALARA

The “as low as reasonably achievable” (ALARA) principle is commonly employed in the fields of radiology and radiation safety to ensure that exposure to ionizing radiation is minimized to the lowest possible levels, given the constraints of economic and social factors. Auto ALARA is an advanced automatic exposure control algorithm. It automatically adjusts the X-ray tube voltage and current so that the subjects will get optimized image quality with minimum radiation dose. Tube voltage was automatically determined via the Auto-kV feature, offering options of 100 kV, 120 kV or 140 kV, while the tube current was optimized using dose modulation (DOM) techniques.

2.2.2 CardioXPhase

Employing CCTA at strategic temporal junctures when cardiac motion is minimized represents a robust strategy for ameliorating motion-induced artifacts. Conventionally, these moments occur during the systolic and diastolic phases, situated at approximately 45% and 75% of the cardiac cycle, respectively for an average heart rate patient. However, the best phase is not guaranteed in real-world scenarios, necessitating a manual intervention for phase selection.

The uCT ATLAS system is equipped with the automatic best phase selection method known as CardioXPhase. This technique is built upon coronary quality evaluation [5]. Specifically, this algorithm consists of four steps. In the first step, a rapid multi-phase reconstruction is performed by employing a small Field of View (FOV) and a reduced matrix size including the coronary artery in its designated FOV. Subsequently, in the second step, the algorithm computes a motion map utilizing the Mean Absolute Difference (MAD) algorithm [6], pinpointing the phase characterized by minimal motion as the baseline phase. It then delineates an optimal phase range, centered around this reference phase. Although the MAD-determined phase may not precisely coincide with the coronary motion, it effectively defines a stable range for the cardiac cycles. Progressing to step 3, CardioXPhase extracts the coronary vessels within each phase across the optimal phase range from step 2, and then subjects them to a rigorous evaluation predicated on metrics such as circularity and sharpness. Lastly, in step 4, the phase exhibiting the highest score is deemed the optimal phase [7].

2.2.3 CardioCapture

In some cases, for example, irregular heartbeat (arrythmia), high heart rates, inability to sustain a breath hold, some motion artifacts may still show up. To mitigate the effects of motion artifacts effectively, the uCT ATLAS incorporates an innovative AI-driven motion correction feature called CardioCapture. The algorithm employs deep learning technology to segment coronary artery trees in adjacent temporal segments and derives motion vector models of coronary motion. It then performs motion correction based on those models to produce motion-free images of the heart.

One key of CardioCapture is to derive the motion vector between different time points in the imaging process. The algorithm first reconstructs the target phase (180° of acquisition data typically in the mid-diastole phase) as the weighted reference and then performs multi-temporal reconstruction with overlapping 180° acquisition data. The algorithm then uses deep learning technology to segment the multi-temporal coronary artery tree. Accurate segmentation of the multi-phase coronary artery tree is essential for the coronary artery motion vector calculation. A specialized V-Net architecture employing dilated convolutions is deployed for the segmentation of coronary arteries [8, 9]. Subsequent to this segmentation, an additional optimization algorithm is executed to derive a smoothed arterial centerline from the segmented mask of the coronary artery. Following this extraction, Coronary artery motion tracking is performed to obtain the coronary motion vector from the adjacent phase to the target phase.

By integrating CardioXPhase and CardioCapture, it becomes possible to conduct CCTA examinations with automatic optimized parameters for each patient. This amalgamation is anticipated to significantly augment both the efficiency and accuracy of these diagnostic tests.

2.3 Evaluation

All imaging data were subject to advanced reconstruction via a commercial hybrid iterative reconstruction algorithm (KARL3D, United-Imaging Healthcare), specifically set at level 3 to mitigate image noise. The optimal cardiac phase was automatically determined by the CardioXPhase function, followed by an additional layer of refinement through the CardioCapture algorithm. Two distinct sets of image series, one originating from an automatically selected cardiac phase and another incorporating supplemental motion correction strategies, were generated for subsequent evaluation.

Importantly, all these computational reconstructions were achieved without requiring manual oversight from a radiologist or cardiologist. To evaluate the performance of this automatic reconstruction method, the image quality is evaluated in this retrospective study. A nuanced four-point Likert scale was deployed to rigorously assess the image quality across each coronary artery segment. This assessment was meticulously performed by two experienced cardiologists and conformed to the rigorous 18-segment coronary artery model. The ensuing analysis was executed on a segment-by-segment basis, ensuring a granular level of scrutiny. The procedure of the evaluation is shown in Figure 1.

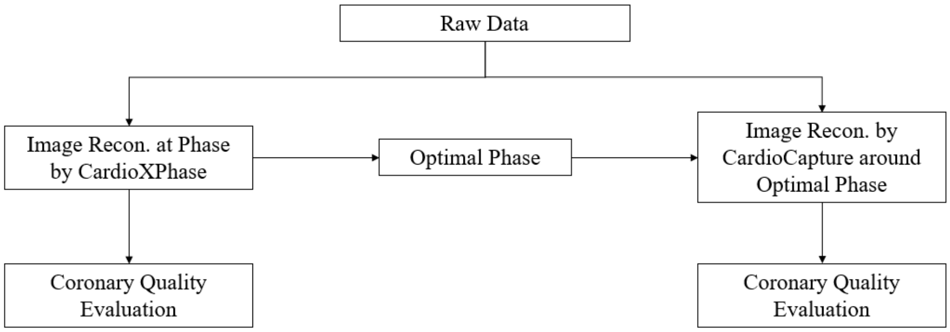

Figure 1. Flowchart Illustrating the Evaluation Procedure. Recon. denotes the image reconstruction.

2.4 Statistical analysis

All statistical investigations were executed utilizing SPSS software (version 22.0; SPSS, Chicago, Ill). Quantitative variables are depicted as mean values accompanied by their standard deviations. The McNemar test was performed to gauge the statistical significance of disparities between paired proportions, where a p-value of less than 0.05 suggests that there is a statistically significant difference between the paired proportions or groups being compared. The agreement between the two cardiologists on the subjective image quality score was assessed using the Cohen kappa test, interpreted as follows: kappa values below 0.20 signified poor agreement; values between 0.21 and 0.40 indicated fair agreement; a range of 0.41 to 0.60 denoted moderate agreement; values within the 0.61 to 0.80 span suggested good agreement; and values from 0.81 to 1.00 manifested excellent agreement.

3. Results

3.1 Evaluation on the auto ALARA

Figure 2 demonstrates auto ALARA-acquired images from two male subjects with different BMIs: one at 43.3 kg/m^2 and the other at 28.8 kg/m^2, both having a heart rate of 79 bpm. For the subject with a BMI of 43.3, auto ALARA fine-tuned the parameters to 140 kV and 660 mA, whereas for the subject with a BMI of 28.8, the optimized settings were 100 kV and 606 mA. Upon visual inspection, both sets of images exhibit comparable image quality, particularly with respect to texture clarity and noise levels.

The radiation dose delivered to patients is influenced by various factors, among which X-ray tube voltage and current are particularly significant. Elevated level current is directly proportional to increased radiation exposure. Voltage is not proportional but positively correlated to radiation exposure. Figure 3 shows the scatter plot of the relationship between BMI and the product of tube voltage (kV) and current (mA) of the subjects in this study. It shows a positive correlation. Overall tendency shows that the higher BMI subject will have higher voltage and current product. This implies the efficacy of the DOM strategy in tailoring imaging parameters to accommodate variations in BMI.

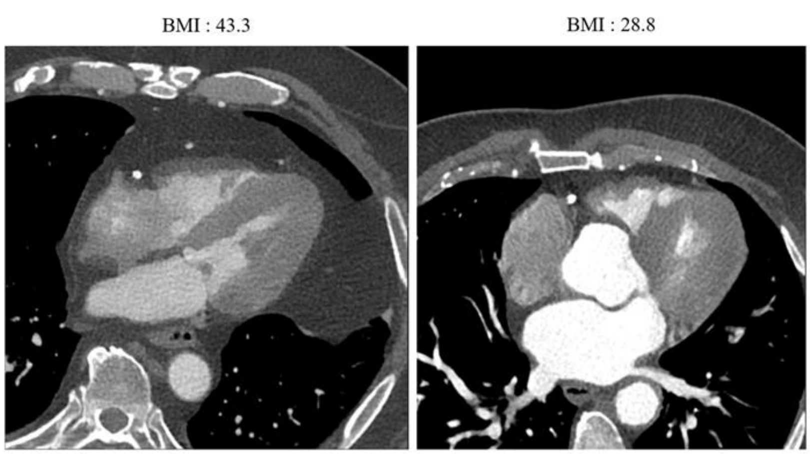

Figure 2. Comparative Imaging Acquired via Auto ALARA for Two Male Subjects with Identical Heart Rates of 79 bpm, Displayed Using a Window Level (WL) of 100 and a Window Width (WW) of 700. All the following CT images used the same display window and will not be emphasized.

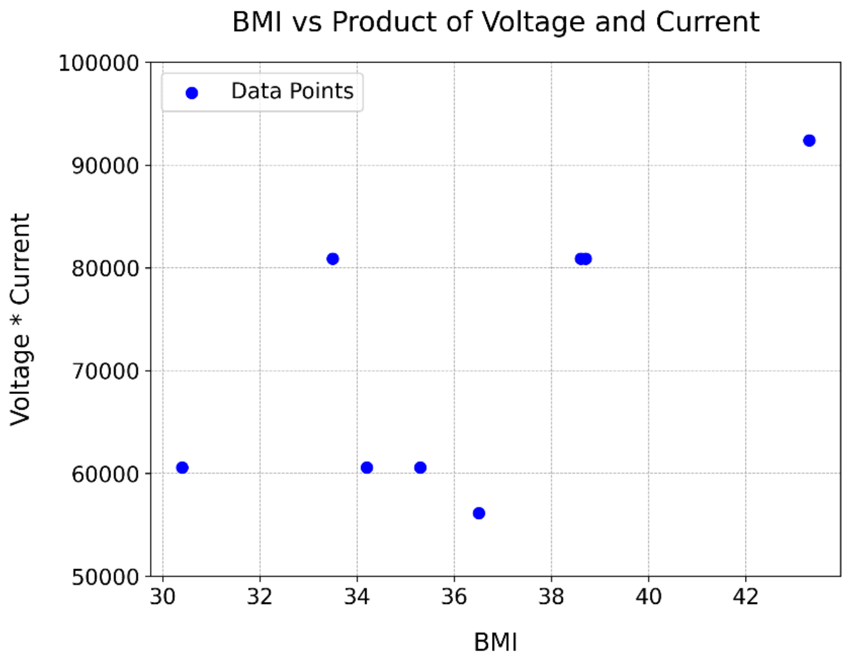

Figure 3. The correlation between BMI and the multiplicative interaction of tube voltage and current within the study cohort.

3.2 Evaluation on the CardioXphase and CardioCapture

3.2.1 Qualitative Evaluation

Adhering to the evaluation procedure presented in Figure 1, two experienced cardiologists assessed the quality of the coronary. Figure 4 shows images generated using CardioXPhase for phase selection and CardioCapture for motion correction. The subject, a male with a BMI of 35.3 kg/m², exhibited a heart rate of 108 bpm. The images demonstrate that CardioXPhase effectively identifies the optimal reconstruction phase for this individual, even with his extremely elevated heart rate. The image quality is already diagnostically reliable, with only minimal motion artifacts present. Subsequent application of CardioCapture further enhances the sharpness of the coronary structures.

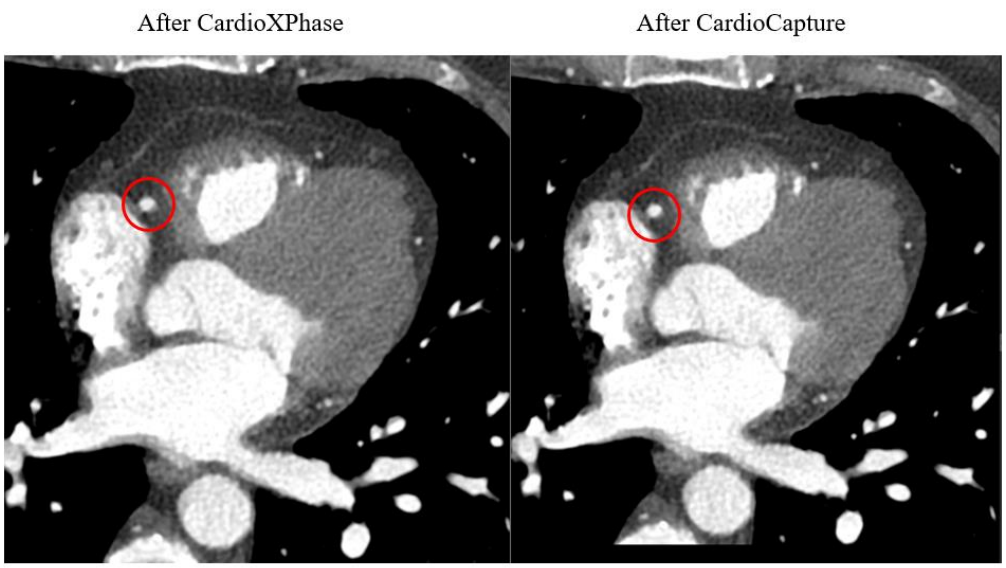

Figure 4. 47-year-old man with heart rate 108 bpm. Left panel: the image after CardioXpahse. Right panel: the image after CardioCapture.

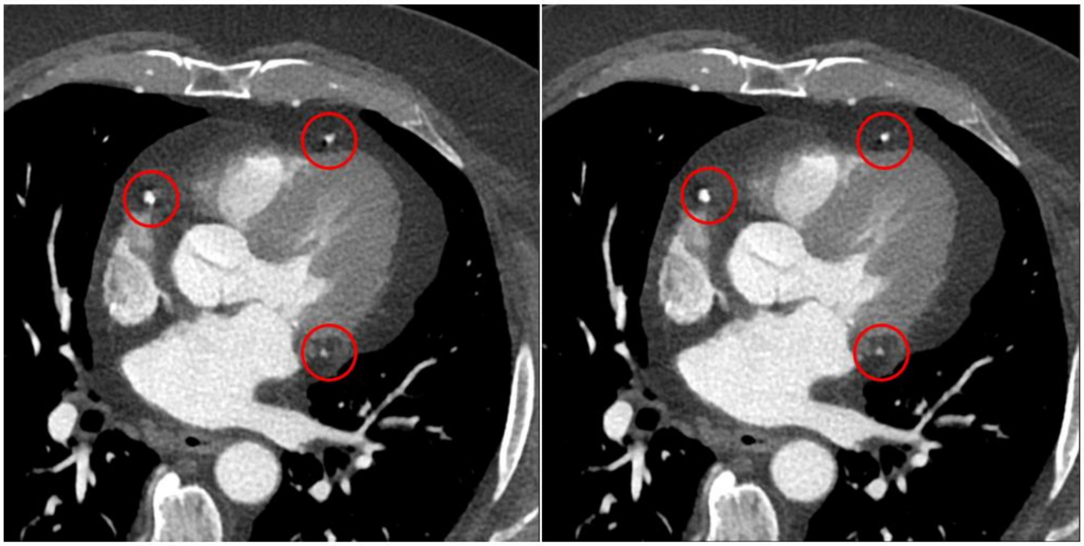

Figure 5. 71-year-old man with heart rate 81 bpm. Left panel: the image after CardioXpahse. Right panel: the image after CardioCapture.

Table 2: Score statistics of four major vessels after CardioXpahse and CardioCapture.

	RCA	LM	LAD	LCX
Mean score after CardioXPhase	2.9	3.3	3.3	2.9
Mean score after CardioCapture	3.7	3.5	3.6	3.6
Mean difference	0.8	0.2	0.3	0.7
p	<0.05	0.21	0.16	<0.05

Figure 5 presents an illustrative example featuring a male subject with a BMI of 38.7 kg/m² and a heart rate of 81 bpm. The images visibly demonstrate the presence of motion artifacts even after the application of the CardioXPhase algorithm. However, these artifacts are significantly reduced upon the subsequent utilization of the CardioCapture algorithm. For easier reference, the coronary arteries of interest have been distinctly highlighted within red circles.

3.2.2 Quantitative Evaluation

A total 124 out of the 144 segments were identified for evaluation in 8 patients with 20 (13.8%) segments being excluded (diameters < 1.5 mm). The subjective consistency of image scoring between two cardiologists was in excellent agreement. After CardioXPhase reconstruction, among the 124 segments, 106 segments (88%) were rated as having diagnostic image quality (scores 2–4) and the average score for all vessels was 3.1 ± 0.37 (Table 2). When CardioCapture was applied, diagnostic segments number became 124 (100%) and the average score is 3.6 ± 0.28.

In four major vessels (RCA, LM, LAD, LCX), CardioCapture results are shown in Table 2. The RCA and LCX depicted significant improvements post-CardioCapture, with mean scores surging from 2.9 to 3.7 and from 2.9 to 3.6, respectively, both reflecting statistical significance with p values less than 0.05. Meanwhile, the LM and LAD, despite showcasing enhancements from 3.3 to 3.5 and 3.3 to 3.6 respectively, did not achieve statistical significance with p-values of 0.21 and 0.16. Notably, the scores for LM and LAD after using CardioXphase had already achieved 3.3, indicating strong diagnostic image quality leaving minimal motion artifacts left for CardioCapture to address.

4. Discussion and Conclusion

In populations characterized by elevated heart rates and high BMIs, this study illuminated the transformative potential of advanced algorithms in enhancing CCTA diagnostic outcomes. The auto ALARA algorithm showcased its adaptability and precision by ensuring consistent image quality across subjects with varying BMIs, reaffirming its utility in such specialized cohorts. The CardioXPhase algorithm was effective in these challenging populations to select the optimal reconstruction phase. CardioCapture proved to be effective to address the motion correction left after CardioXPhase, particularly in boosting image quality for the RCA and LCX vessels. Collectively, these findings emphasize the significance and potential of tailoring advanced algorithms for CCTA to address the unique challenges posed by patients with high heart rates and elevated BMIs. The complexity inherent in the CCTA scanning workflow could be significantly streamlined given these advanced algorithms.

While our study engaged a limited group of eight participants, it's essential to note that we assessed a substantial 144 segments of the coronary arteries. This granularity offers a broader context than the participant count might suggest. Given our specific focus on extreme cases, such as those with rapid heart rates and elevated BMIs, the findings hold significant value. Expanding this evaluation to a larger population would be one of our future interests.

5. Image/Figure Courtesy

All images are the courtesy of Carrollton Regional Medical Center, Dallas, Texas.

6. References

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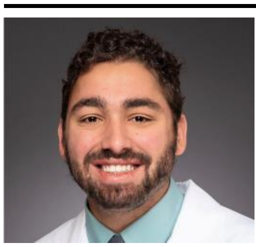
Nishant Surapaneni is a third-year medical student at NEOMED with a vibrant background in biology and biotechnology from the University of Southern California. As a co-founder and board member of Inhale on Motorola, Nishant has demonstrated his entrepreneurial acumen by co-developing a product that monitors air quality for patients with respiratory distress. His success in fundraising and strategic partnership cultivation has positioned the venture at the forefront of technological innovation in healthcare.

Beyond his start-up endeavors, Nishant's expertise extends to healthcare mergers and acquisitions with Oracle USA, and as a financial analyst for SANA Healthcare, he has deepened his understanding of the financial facets of healthcare delivery. His professional journey reflects a commitment to enhancing patient care through technological advancements, pursuing a blend of medical knowledge and technological innovation.



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