ISSN: 2230-9926

*Available online at http://www.journalijdr.com*

IJDR

*International Journal of Development Research*
*Vol. 13, Issue, 07, pp. 63296-63300, July, 2023*
**https://doi.org/10.37118/ijdr.26962.07.2023**

**RESEARCH ARTICLE** **OPEN ACCESS**

# CARDIAC FITNESS INDEX BASED ON TREADMILL HR MONITORING: ITS NOVELTY, PROVIDING CARDIAC DIAGNOSTICS IN TERMS OF CORRELATION OF CFI WITH LV EF, AND ENABLING MEDICAL MANAGEMENT OF THE SUBJECT

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## ARTICLE INFO

***Article History:***
Received 14th April, 2023
Received in revised form
20th May, 2023
Accepted 26th June, 2023
Published online 30th July, 2023

***KeyWords:***

Cardiac Fitness, Heart Rate, Left Ventricle, Electrocardiogram, Ejection Fraction.

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## ABSTRACT

In a medical clinic, cardiologists monitor the cardiac health of patients by monitoring their heart rate while on the treadmill and after the patient has gone off the treadmill. However, they only monitor their heart rate values, and not the trend of the heart rate variation. Then, if their heart rate goes up very fast, and to very high values, it is an indication of cardiac dysfunction, for which further tests are recommended. However, this is an empirical and subjective assessment of a patient's heart function assessment. In our opinion, we need to know (i)the rate at which the heart rate keeps increasing while walking on the treadmill, and (ii) the rate at which it keeps decreasing off of the treadmill, to help us accurately determine the health state of a patient's heart. For this purpose, we need to fit mathematical equations to simulate the monitored heart rate vs time data, while on and off the treadmill. In order to quantitively characterize cardiac fitness, we need to develop an index which describes the trend of heart rate variation while striding on the treadmill and after getting off the treadmill. In this paper, we have first determined the heart rate variation equations. The equation for heart rate variation while striding on the treadmill is given by$HR = HRo \times t^{k1}$, where $HRo$ is the initial heartrate when getting on the treadmill. Then the equation for heart rate variation after getting off the treadmill is given by $HR = HRe \times t^{-k2}$, where HRe is the heart rate reached at the end of striding on the treadmill. Among our four subjects, the range of $k1$ was found to be 0.2 to 0.25. The range of $k2$ was found to be -0.2 to -0.3. Then we have formulated the Cardiac Fitness Index (CFI) as follows:

$$CFI = \frac{k2}{k1} \times \frac{HRo}{(HRe - HRo)} \times \frac{(HRe - HRf)}{HRe} \times 100$$

wherein $HRo$ is the initial rate at the time of getting on the treadmill, $HRe$ is the heart rate at the end of 10 minutes on the treadmill, and $HRf$ is the final value of the heart rate at 10 minutes after getting off the treadmill. We have evaluated four patients and calculated the values of their CFIs. Based on this, we found the range of CFI to be from 87 to 34.Now our intent is to monitor more subjects and find out the CFI ranges for normal subjects and subjects with cardiac symptoms. This can enable the cardiologist to diagnose a subject with cardiac issues and recommend the subject for further tests, to determine the precise nature of the cardiac problem. For this purpose, we are proposing that for these patients, we also monitor their ejection fraction (EF) noninvasively by echocardiography. Then, the novelty of CFI in denoting the cardiac health of a subject, can be obtained by corelating the CFI with the noninvasive echocardiographic measurement of ejection fraction of patients. By determining this correlation, the patient's health can be monitored very conveniently and accurately by just determining the CFI. Then our Cardiac Fitness Index (CFI) can be employed very effectively by cardiologists to assess the cardiac health state of patients. In fact, it can also be people at home to determine the cardiac fitness, and to stay fit. Thus, our paper will enable both medical and non-medical people to assess their cardiac fitness, and hence will have a wide range of applications.



**Citation:** ***Dhanjoo Ghista, Ronit Kapoor, Siva Mullapudi, Vara Wuyyuru and Prashanth Nyalakanti. 2023.*** "Cardiac fitness index based on treadmill hr monitoring: its novelty, providing cardiac diagnostics in terms of correlation of CFI with LV EF, and enabling medical management of the subject". *International Journal of Development Research*, 13, (07), 63296-63300.

# INTRODUCTION

The Heart and the Left ventricle, Heart's Electrical system, and Coronary Artery system

Figure 1 illustrates the heart, aorta, pulmonary artery, and the coronary arteries. The coronary arteries supply blood and oxygen to the heart chambers' myocardium. A well perfused myocardium enables the myocardium to contract efficiently, and to have a high ejection fraction. This can also denote good cardiac fitness. Figure 2 depicts the four chambers of the heart. The Purkinje fibers are specialized electrical conducting fibers composed of electrically excitable cells. The Purkinje fibers allow the heart's conduction system to create synchronized contractions of its ventricles, and are hence essential for maintaining a consistent heart rhythm. Figure 3. displays the coronary arteries surrounding and penetrating the walls of the heart chambers. The coronary vessel branches penetrate the heart chambers' walls and perfuse them with blood and oxygen. This enables the heart chambers to contract and eject the blood.

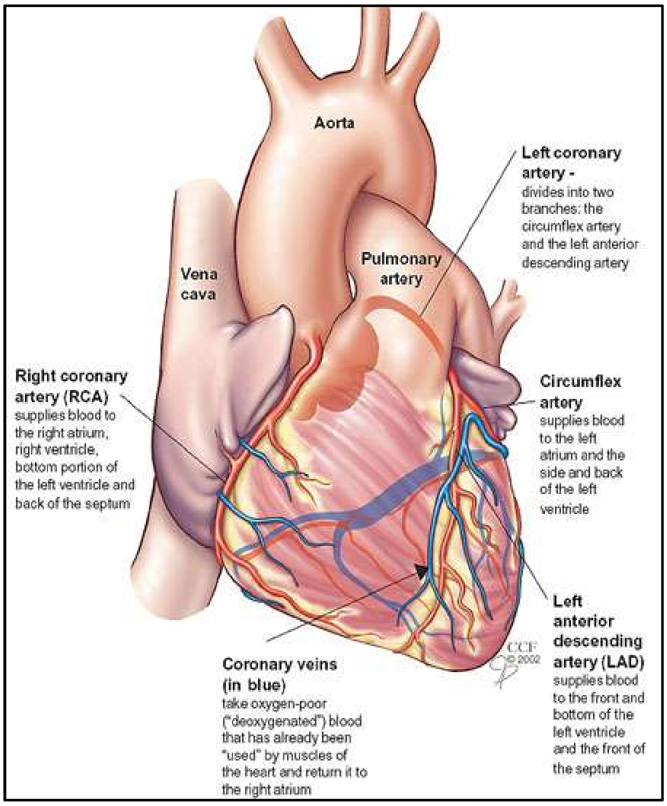


**Figure 1. The Heart, Aorta, Pulmonary artery, Coronary arteries engulfing the heart**

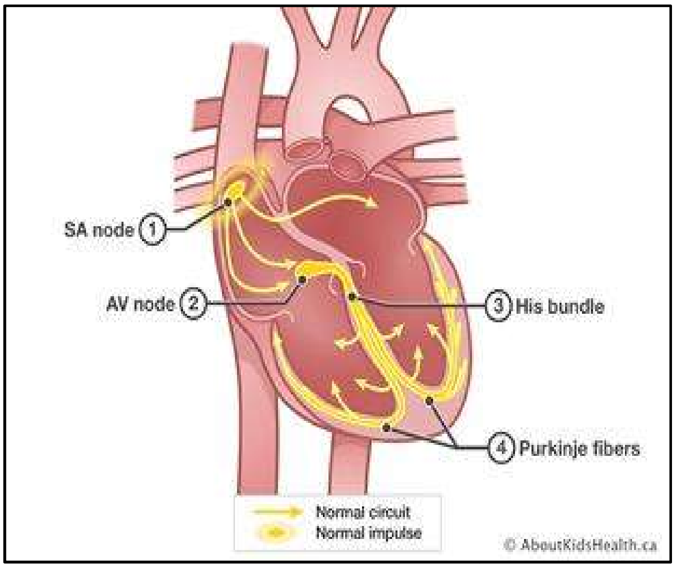


**Figure 2. The four chambers of the heart, and the Purkinje fibers**

***Exercise Stress Test on the Treadmill:*** An exercise stress test shows how your heart works during physical activity. Because exercise makes your heart pump harder and faster, an exercise stress test can reveal problems with blood flow within your heart. Your doctor may recommend a stress test if you have signs or symptoms of coronary artery disease or an abnormal heart rhythm (arrhythmia).

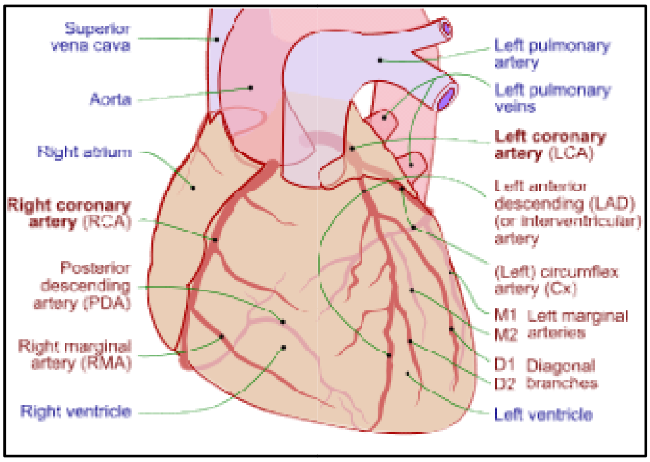


**Figure 3. Coronary arteries perfusing the heart**

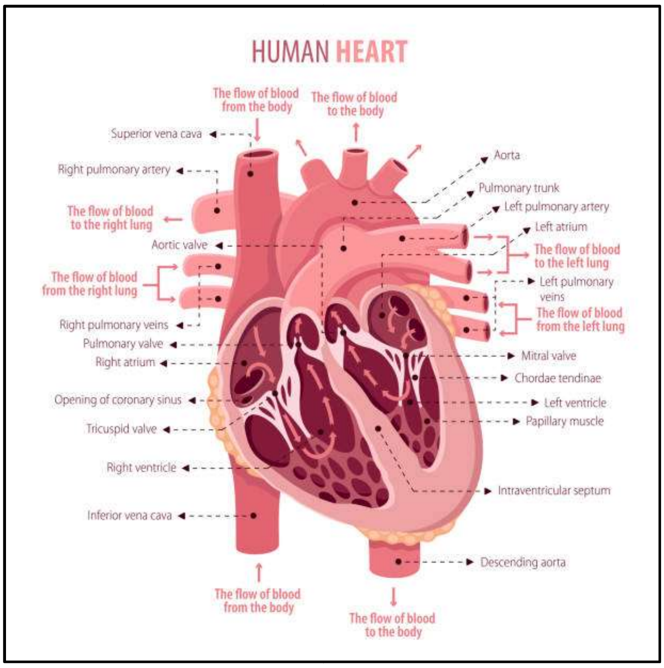


**Figure 4. Detail picture of the heart chambers, heart structures, heart valves, and blood vessels**

**Figure 5. Stress Test on the Treadmill**

**Your doctor may recommend a stress test to:**

**(i)** Diagnose coronary artery disease: Your coronary arteries are the major blood vessels that supply your heart with blood, oxygen, and nutrients. Coronary artery disease develops when these arteries become damaged or diseased — usually due to a buildup of deposits containing cholesterol and other substances (plaques).

**(ii)** Diagnose heart rhythm problems (arrhythmias): Heart arrhythmias occur when the electrical signals that coordinate your heartbeat don't work properly. An arrhythmia can cause your heart to beat too fast, too slowly or irregularly.

**(iii)** Guide treatment of heart disorders: If you've already been diagnosed with a heart condition, an exercise stress test can help your doctor determine if your current treatment is working. The test results also help your doctor decide on the best treatment for you.

# RESULTS

If the information gathered during your exercise stress test shows your heart function to be normal, you may not need any further tests. However, if the results are normal and your symptoms continue to worsen, your doctor might recommend (i) a nuclear stress test or another stress test that includes an echocardiogram before and after exercise, or (ii) medications to increase blood flow to your heart. These tests are more accurate and provide more information about your heart function, but they are also more expensive. If your stress test results suggest that you might have coronary artery disease or show an arrhythmia, your doctor will use the information to develop a treatment plan. You may need additional tests, such as a coronary angiogram (described in Appendix B) to determine the degree of coronary stenosis.

**Cardiac Fitness Index:** based on Treadmill Heart Rate monitoring and its Mathematical Simulation, to be made into a smart CFI device.

This Section is based on our paper Reference 3.

**Figure 6. Subject jogging on the Treadmill, while monitoring his heart rate**

In medical clinics, cardiologists have their patients get on the treadmill and monitor their heart rate. Then, if their heart rate goes up very fast, and to very high values, it is an indication of cardiac dysfunction. For that, the cardiologist recommends further tests (as described above), such as a cardiac echogram or even a coronary angiogram to determine the cause of cardiac dysfunction. So, after the Exercise Stress test, if the heart rate goes up very fast, no specific diagnostics is made, and the patient with symptoms of cardiac dysfunction has to undergo further elaborate tests to determine the cause of cardiac dysfunction.

**On the other hand, our proposed Cardiac Fitness Index (CFI) can provide a specific value of cardiac dysfunction**: For that, we monitor the heart rate increasing while walking on the treadmill, and the heart rate decreasing after getting off the treadmill. We then determine the CFI value based on the below formula (1).

$$CFI = \frac{k2}{k1} \times \frac{HRo}{(HRe-HRo)} \times \frac{(HRe-HRf)}{HRe} \times 100 \quad (1)$$

which involves determination of the expressions for:

**(i)** Heart rate variation on the treadmill: $HR = HRo \times t^{k1}$ (2)
where $HRo$ is the initial heart rate and $HRe$ is the heart rate at the end of the tread mill session.

**(ii)** Heart rate variation after getting off the treadmill: $HR = HRe \times t^{-k2}$(3)

with the final heart rate coming down to $HRf$,

Figure 7 shows the tracings of monitored heart rate, and the expressions simulating the monitored Heart Rates on and off the treadmill.

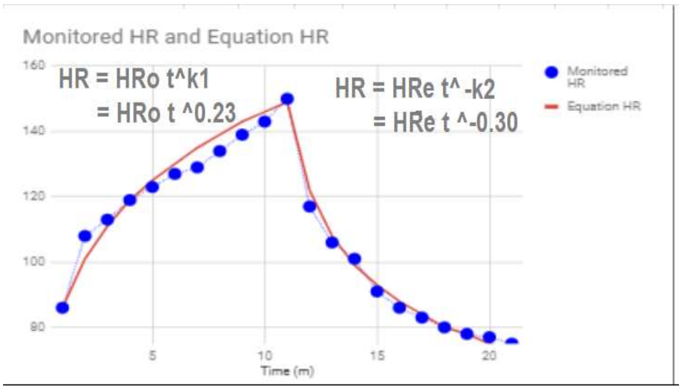


**Figure 7. For Subject RK: (i) Tracings of monitored heart rate (blue dots), (ii) Equations simulating the monitored heart rates on and off the treadmill, (iii) Red curves based on the simulated equations, showing how closely the red curves depict the heart rate variations of the blue dots**

So in Figure 7, we are showing for subject RK (i) Heart Rate data tracings while on and off the treadmill, (ii) Equations of Heart Rate variations fitting the data. Then in Table 1, we can observe the differences between the monitored heart rate and the heart rate given by these equations, as expressed by the percentage errors. In this Table 1, we can see the monitored heart rate values over ten minutes, from initial Heart Rate ($HRo$) to end Heart Rate ($HRe$) in ten minutes. In the next row, we are seeing the values of the simulated equation $HR = HRo \times (t^{0.23})$, which was derived to minimize the sum of the differences between the calculated and monitored HR values, as shown in the next row.

**Table 1. Heart Rate Data of subject RK when on and off the treadmill, and Differences between the monitored HR and HR given by the simulated expressions**

While on the treadmill, the monitored HR increases from initial $HRo$ =86 to $HRe$ = 150 in ten minutes. The simulated equation is $HR =$

$HRo \times (t^{0.23})$, for which we are seeing that the sum of the differences is very small.

| RK on the treadmill | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time (m) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | |
| Monitored HR | 86 | 108 | 113 | 119 | 123 | 127 | 129 | 134 | 139 | 143 | 150 | |
| HR = HRo t^0.23 | 86 | 101 | 111 | 119 | 125 | 130 | 135 | 139 | 143 | 146 | 149 | |
| Difference | 0 | 7 | 2 | 0 | -2 | -3 | -6 | -5 | -4 | -3 | 1 | Sum = -13; Error = 10 %; Error per time = 1.3 |

Next after getting off the treadmill, we are seeing the monitored HR values going down from $HRe = 150$ to $HRf = 75$. The simulated equation is $HR = HRe \times (t^{-0.3})$, for which we are seeing that the sum of the differences is very small.

| RK off the treadmill | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time (m) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | |
| Monitored HR | 150 | 117 | 106 | 101 | 91 | 86 | 83 | 80 | 78 | 77 | 75 | |
| HR = HRe t^-0.3 | 150 | 122 | 108 | 99 | 93 | 88 | 84 | 80 | 78 | 75 | 73 | |
| Difference | 0 | -5 | -2 | 2 | 2 | 2 | 2 | 0 | 0 | 2 | 2 | Sum = 5; Error = 2.3%; Error per time = 0.5 |

This is what CFI calculation involves, based on Equation (1). The primary involvement is in the determination of the expressions of HR variation while on the treadmill and after getting off the treadmill, as given by equations (2) and (3). Next in Figure 8, we are showing the monitored and simulated curves for HR of all the four subjects. We can notice the differences between these four subjects in their HR variations on and off the treadmill, and also the differences in the simulated expressions of HR.

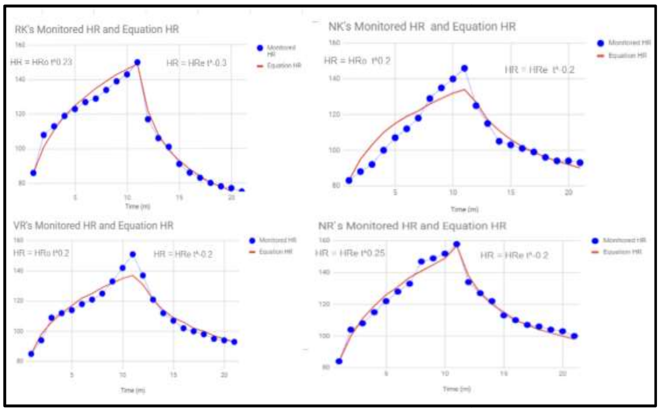


**Figure 8. The graphs of monitored and simulated Heart Rate of all four subjects. We can see the differences between these four subjects in their HR variations on and off the treadmill, and also the differences in the simulated expressions of HR**

**Computed CFI results of all the four subjects:** Now in Table 2 we are showing for all the four subjects, the values of (i) parameters $k2$ and $k1$, (ii) expressions $\frac{HRo}{(HRe-H\ \ )}$ and $\frac{(HRe-HRf)}{HRe}$ and (iii) the final values of CFI. We can see that the main difference between the subjects is in the value of $\frac{(HRe-HRf)}{HRe}$. In other words, for subject RK, the heart rate came down to its normal value in ten minutes, whereas for the other subjects, the $HRf$ did not come down to the normal value of $HRo$.

So now if we apply this formulation of CFI to a wide range of subjects and especially elder subjects, we will be able to see how their heart rate goes up while on the treadmill and comes down when off the treadmill, and how it affects the value of their CFI. This simple formulation will help cardiologists to differentiate normal and fit subjects and unfit subjects who may have a cardiac dysfunction, such as, high blood pressure, arrhythmias, coronary artery disease, and myocardial ischemia. So far, we have monitored four young subjects and even for them we have been able to show a big range in the values of CFI. If now, we were to monitor adults, and even people in a high age group, we think that our Cardiac Fitness Index will have a big range of values for adults.

**Table 2. Results of the four subjects, showing the values of the values of (i) parameters $k2$ and $k1$, (ii) expressions $\frac{HRo}{(HRe-HRo)}$ and $\frac{(HRe-HRf)}{HRe}$, and (iii) the final values of CFI**

| Index Results | | | | | |
|---|---|---|---|---|---|
| Name | k2 | k1 | HRo / (HRe - HRo) | (HRe - HRf) / HRe | Final |
| RK | 0.3 | 0.23 | 1.34 | 0.5 | 87 |
| NK | 0.2 | 0.2 | 1.32 | 0.36 | 48 |
| VR | 0.2 | 0.2 | 1.29 | 0.38 | 49 |
| NR | 0.2 | 0.25 | 1.14 | 0.37 | 34 |

# CONCLUSION

It is now our decision that we apply this formulation of CFI to a wide range of adult subjects. We will hence be able to show that our cardiac fitness index is able to distinctly depict healthy subjects, unhealthy subjects, and subjects who are at risk of heart failure. Now this formulation will be helpful to cardiologists world-wide, in enabling them to detect patients that risk for heart failure. Further, for more efficacious employment of our CFI, we can even develop a software for automated computation of CFI, to be then made into a CFI device.

**The cardiac health state of a person reflected by LV Ejection Fraction, and based on Coronary Artery health or stenosis:** As indicated above (in Section I), blood perfusion from the coronary artery into the LV myocardium enables it to contract, provide adequate stroke volume into the aorta, resulting in adequate ejection fraction (EF) = fraction of the LV blood volume ejected into the aorta. Now if some coronary vessels get occluded, then there is inadequate blood perfusion to the LV myocardium. This impairs the LV contractility, and reduces LV EF from its normal value of 0.55-0.65 to its reduced value of 0.5-0.4.

**Developing the Graph corelating CFI values with LV Ejection Fraction, for patients:** Our next step is to work with cardiologists to monitor patients on the treadmill and determine their CFI values, and to also determine their left ventricular ejection fraction (EF) values, as displayed by the below graph in Figure 9. Based on this graph of CFI vs EF, the CFI values can be directly correlated with EF, cardiac contractility state, and LV myocardial state, and hence with the cardiac medical state of the patients, as depicted on the X axis of the graph. The Left ventricular ejection fraction (LVEF) measures left ventricular systolic function, in the form of fraction of volume ejected in systole (stroke volume) in relation to the LV volume at the end of diastole. For that purpose, we can employ References 1 and 5for the noninvasive method of LVEF determination by Echocardiography. A normal well-contracting LV, with a healthy coronary arterial system, will have a normal ejection fraction of about 0.5 to 0.7, according to the American Heart Association. When some coronary arteries become stenosed, the blood supply to the LV myocardium becomes impaired, the LV contractility is reduced, and correspondingly the LV EF is reduced. A borderline ejection fraction can range between 0.4 to 0.5, and it would be associated with mild coronary arterial stenosis and myocardial ischemia. Then ejection fraction less than 0.4 would imply severe coronary stenosis and myocardial infarction with risk of heart failure.

During this process of monitoring the patients' HR, and determining the patients' CFI value as well as the LV EF, let us say that patients' CFI values fall between these two curve lines of the Graph (Figure 9). Now the decrease in EF is due to decrease in LV contractility (as determinable by our work cited in References 2,4and 8), which in turn is due to myocardial ischemia leading to myocardial infarction, caused by increasing stenosis of coronary artery (as determined by our work cited in References 6 and 7).

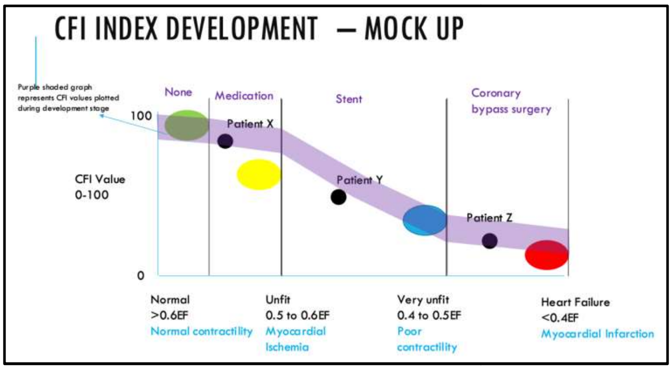


**Figure 9. CFI vs EF, LV contractility, and Myocardial disease. This is what the CFI device will portray on the treadmill stand, showing the relationship of CFI with subject's fitness (top row), EF (middle row), myocardial contractility and disease (bottom row). The monitored subjects' CFI are displayed by black dots, by which the subjects' health state can be designated. So even at home, a subject can use the CFI device to determine her/his CFI value, and then see her/his black dot location on this graph, which will then depict her/his health state.**

This graph can define the correlation between (i) CFI and Left ventricular EF, (ii) CFI andLV contractility, (iii) CFI and myocardial ischemia/infarction, due to the degree of coronary artery stenosis. Now, for correlation with CFI, the ejection fraction (EF) is the most direct and easy to determine measure of cardiac functional integrity. It will also be easier and less complicated to corelate CFI with noninvasively determinable Left ventricular (LV) EF by Echocardiography (References 1 and 5), than with (i) Left Ventricular Contractility Index, based on our work (References 2, 4and 8) and (ii) Coronary Artery stenosis degreeby coronary angiogram based on our work (References 6 and 7).

**Now we want to develop a CFI device that can be attached to the Treadmill:** This CFI device will display this graph of CFI vs EF. Then if a patient's CFI is determined from the device or if a patient determines her/his CFI value at home using this device, then the horizontal line from the CFI value on the Y axis will automatedly cut the two curves, to depict the medical state of the patient.

**This will be the novelty of our CFI device**, to be able to correlate CFI with LV EF, and thereby quantify the medical state of a patient in a medical clinic. The CFI device will also enable a subject at home to keep track of her/his health state.

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