millimetrata al digitale: evoluzione storica e ritorno all’ECG «vero»

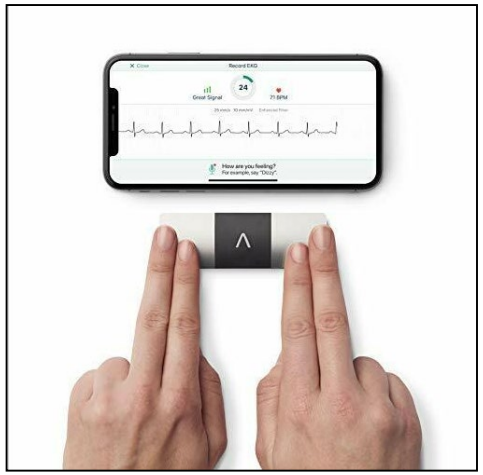
Fabio Badilini, PhD

3 Giugno 2026

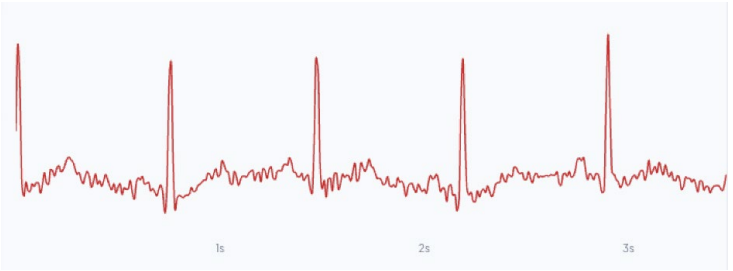
Center for **B**iosignal **R**esearch (CBR)

UCSF Cardiology
Department of Medicine

Ma cosa è l'ECG «vero»?



Casana



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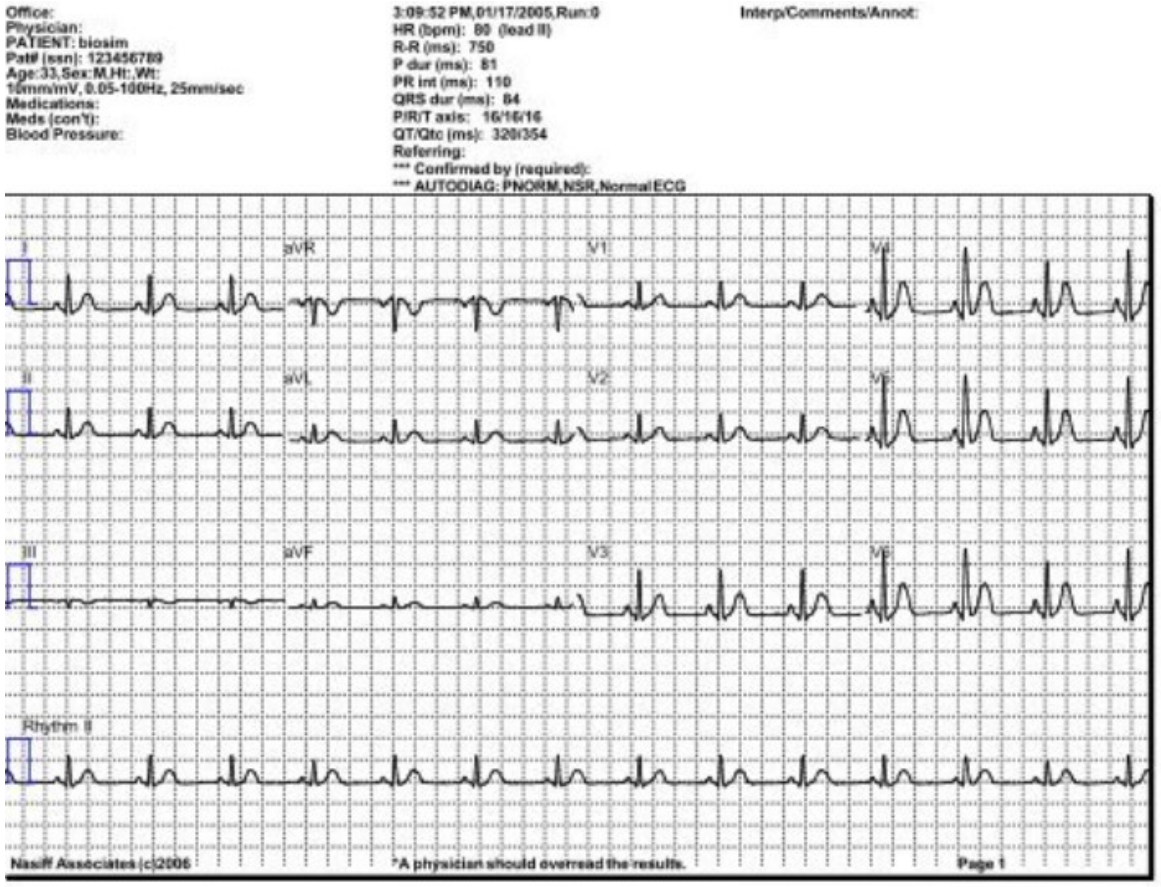
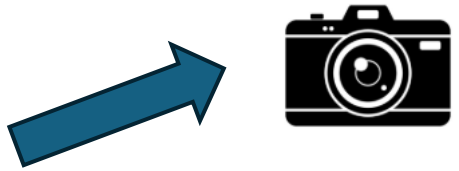
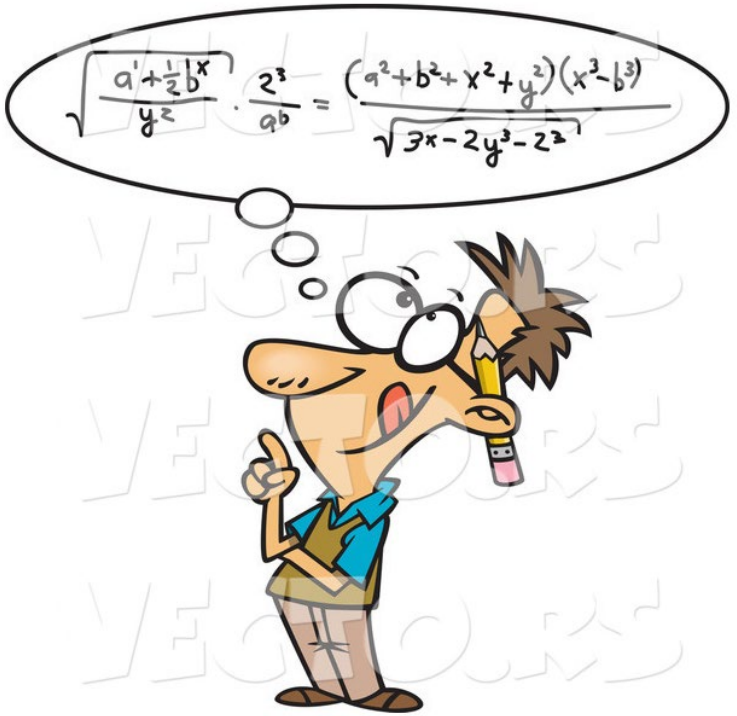




Ma cosa è l'ECG «vero»?
E chi dovrebbe dare la risposta?

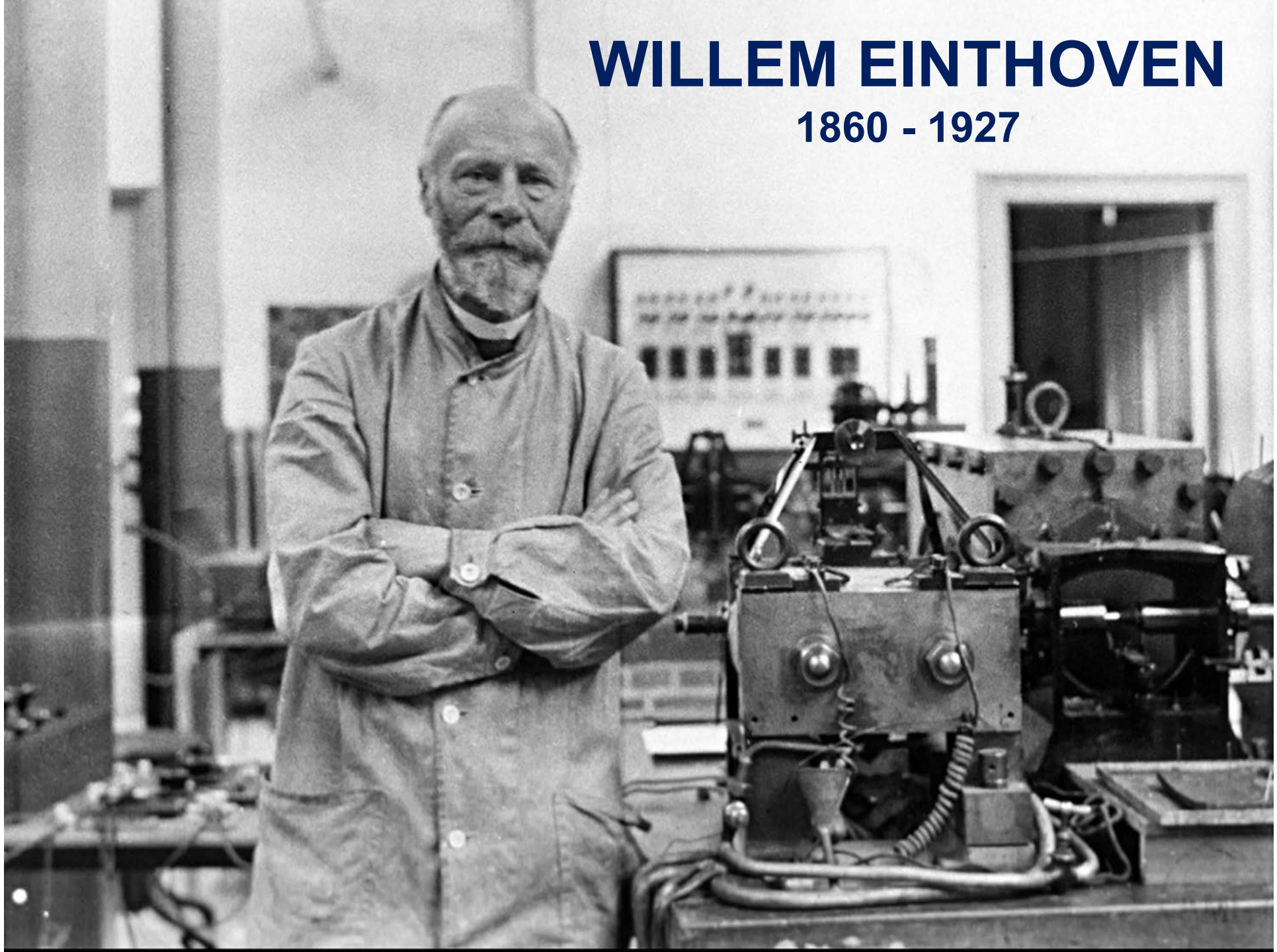


Ma quale clinico?

Ma quale ingegnere?

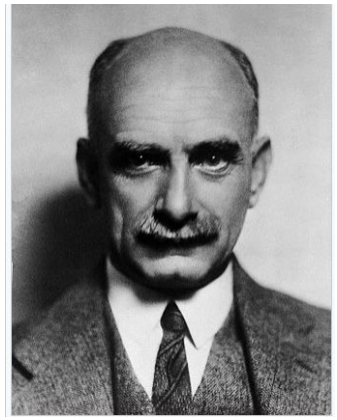
WILLEM EINTHOVEN

1860 - 1927



THOMAS LEWIS

1881 - 1945



THE MECHANISM

OF

THE HEART BEAT

WITH ESPECIAL REFERENCE TO ITS
CLINICAL PATHOLOGY

BY

THOMAS LEWIS, M.D., M.R.C.P., D.Sc.,

Lecturer in Cardiac Pathology, University College Hospital Medical School.

Physician to Out-Patients, City of London Hospital for Diseases of the Chest.

LONDON:
SHAW & SONS, FETTER LANE, FLEET STREET, E.C.,
Printers and Publishers.

1911

1911

CLINICAL

ELECTROCARDIOGRAPHY

BY

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1913.

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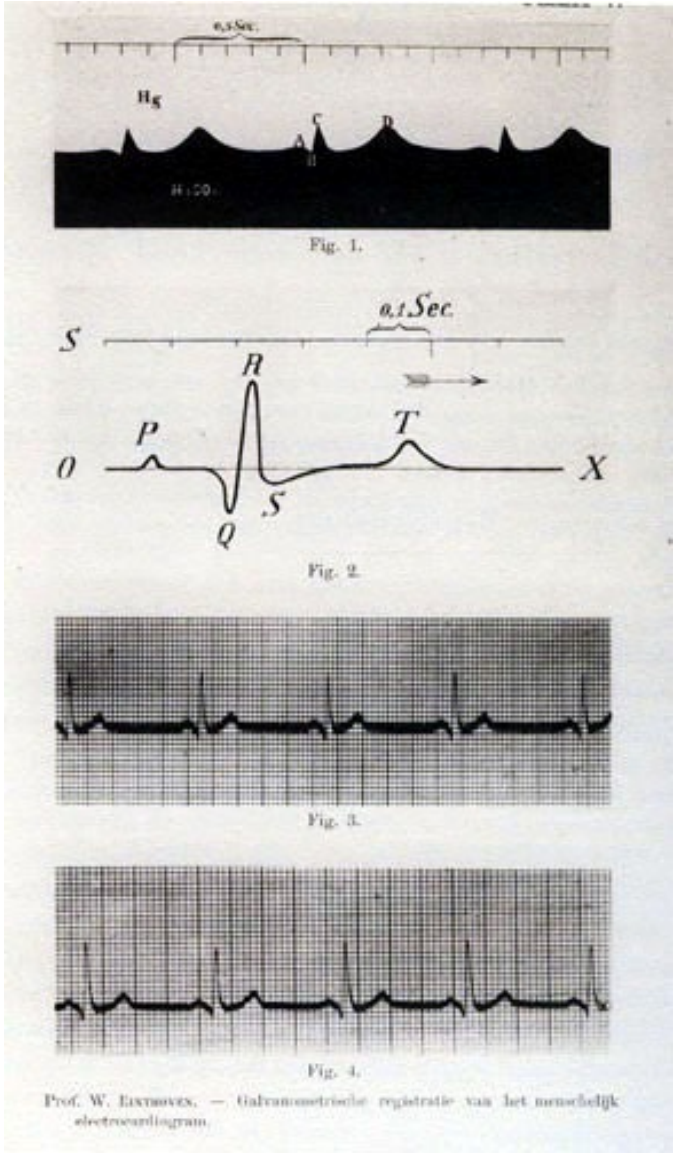
EINTHOVEN 1902



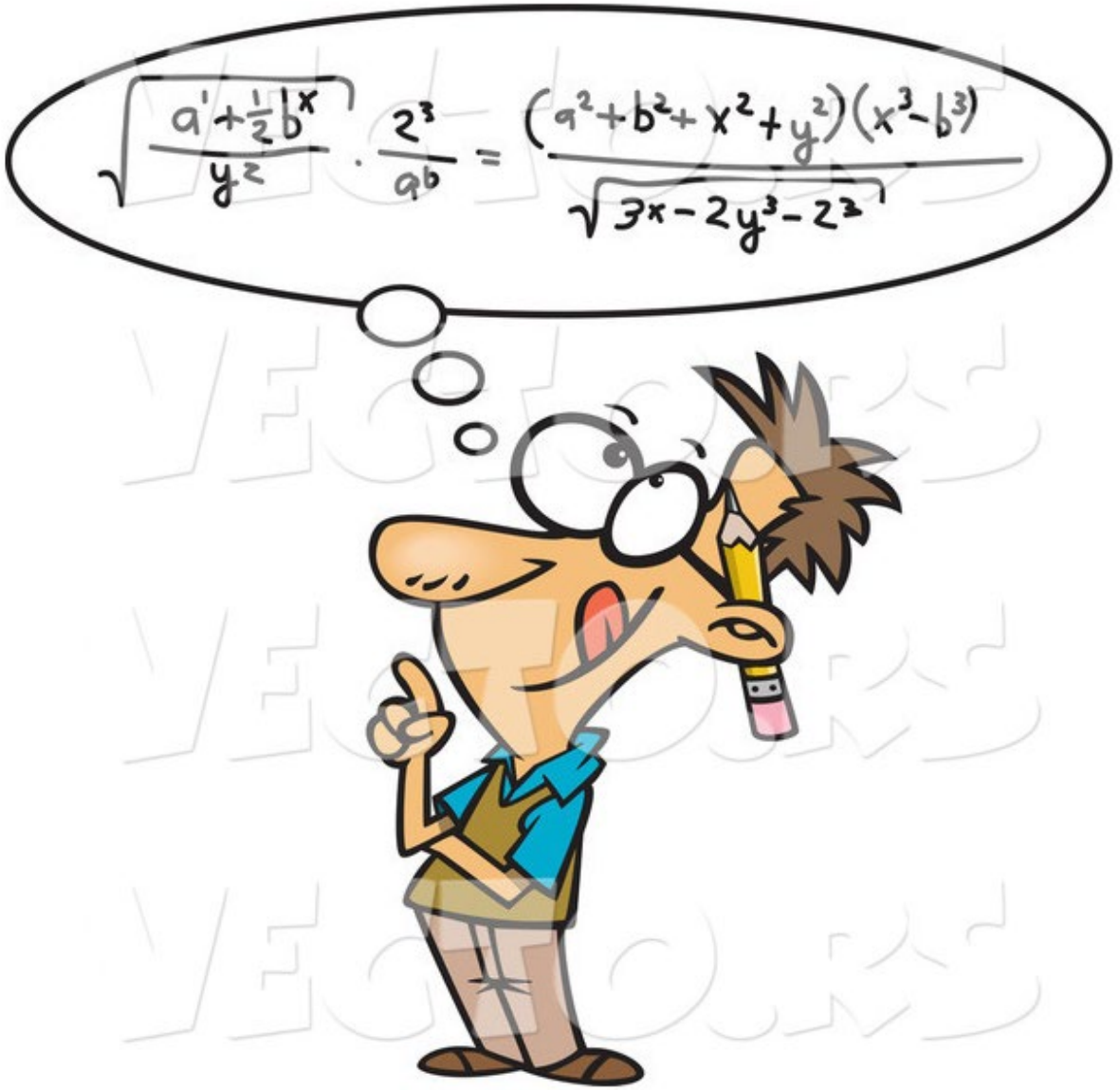
← Elettrometro capillare

← Tracciato “Corretto”

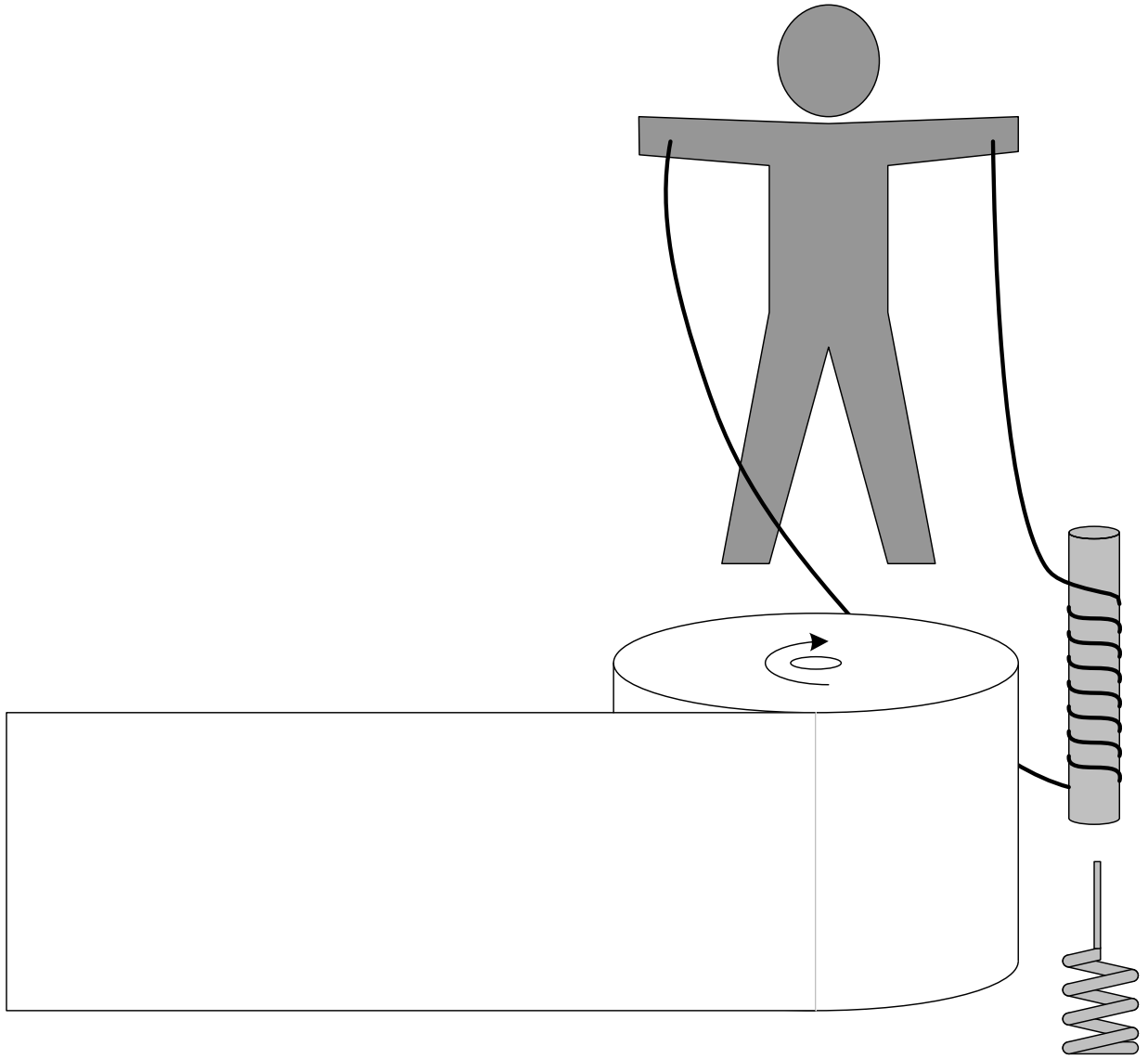
← Galvanometro a corda

Prima pubblicazione di un elettrocardiogramma su umano

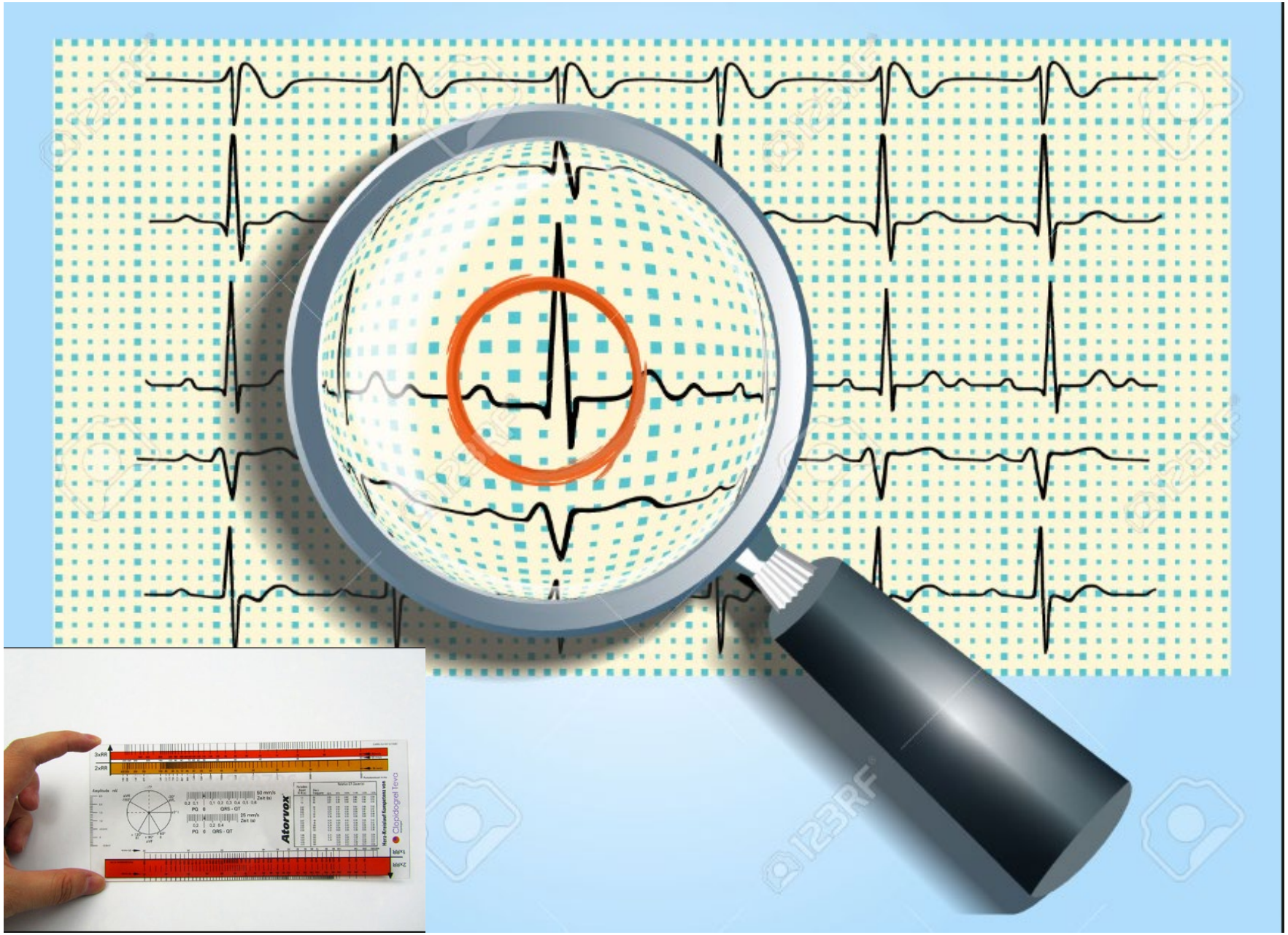
Cosa è quindi l'ECG «vero» secondo l'ingegnere biomedico?



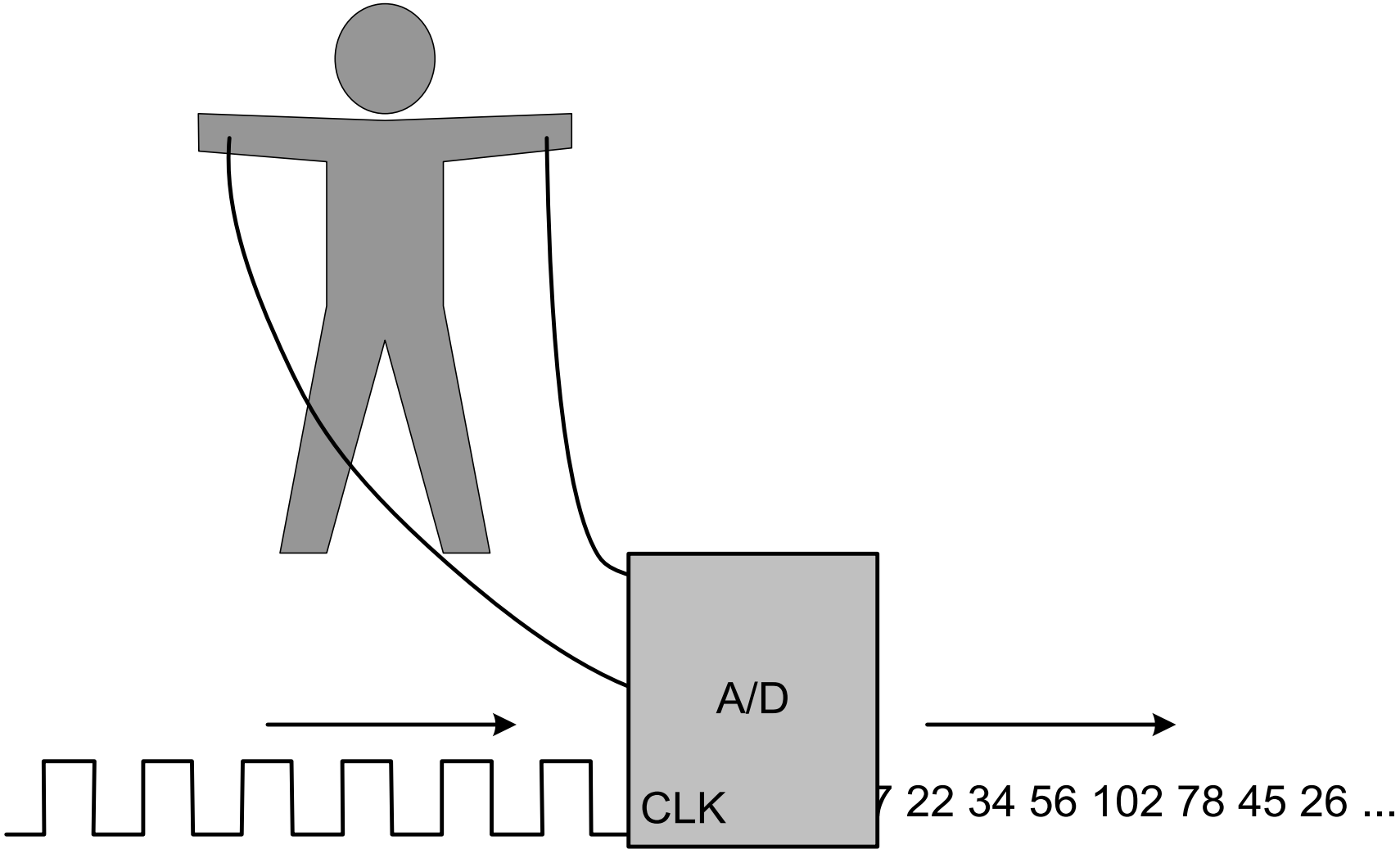
ECG Analogico



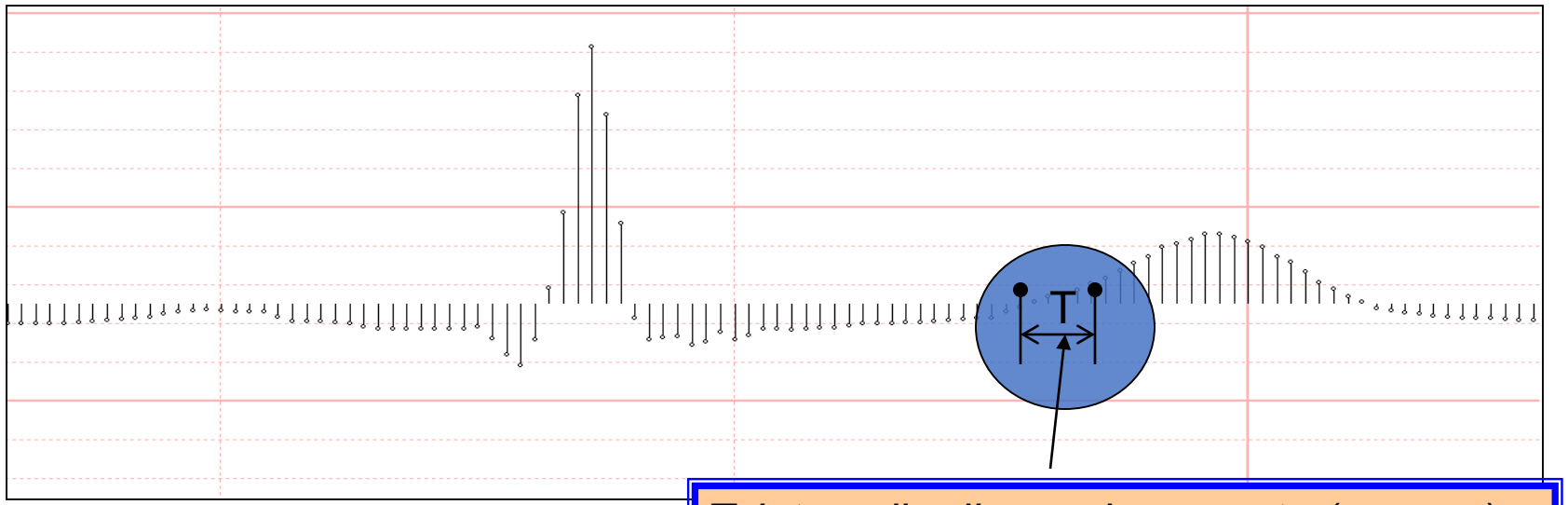
Misurare un ECG analogico



ECG Digitale



Risoluzione Temporale di un ECG Digitale:
Frequenza di Campionamento



T: intervallo di campionamento (s, o ms)
f = 1/T: frequenza di campionamento (Hz)

più piccolo è T (più grande è f) e
maggiore è la risoluzione temporale dell'ECG

Esempio 1: T = 5ms, f = 200Hz (bassa risoluzione)

Esempio 2: T = 1ms, f = 1000Hz (alta risoluzione)

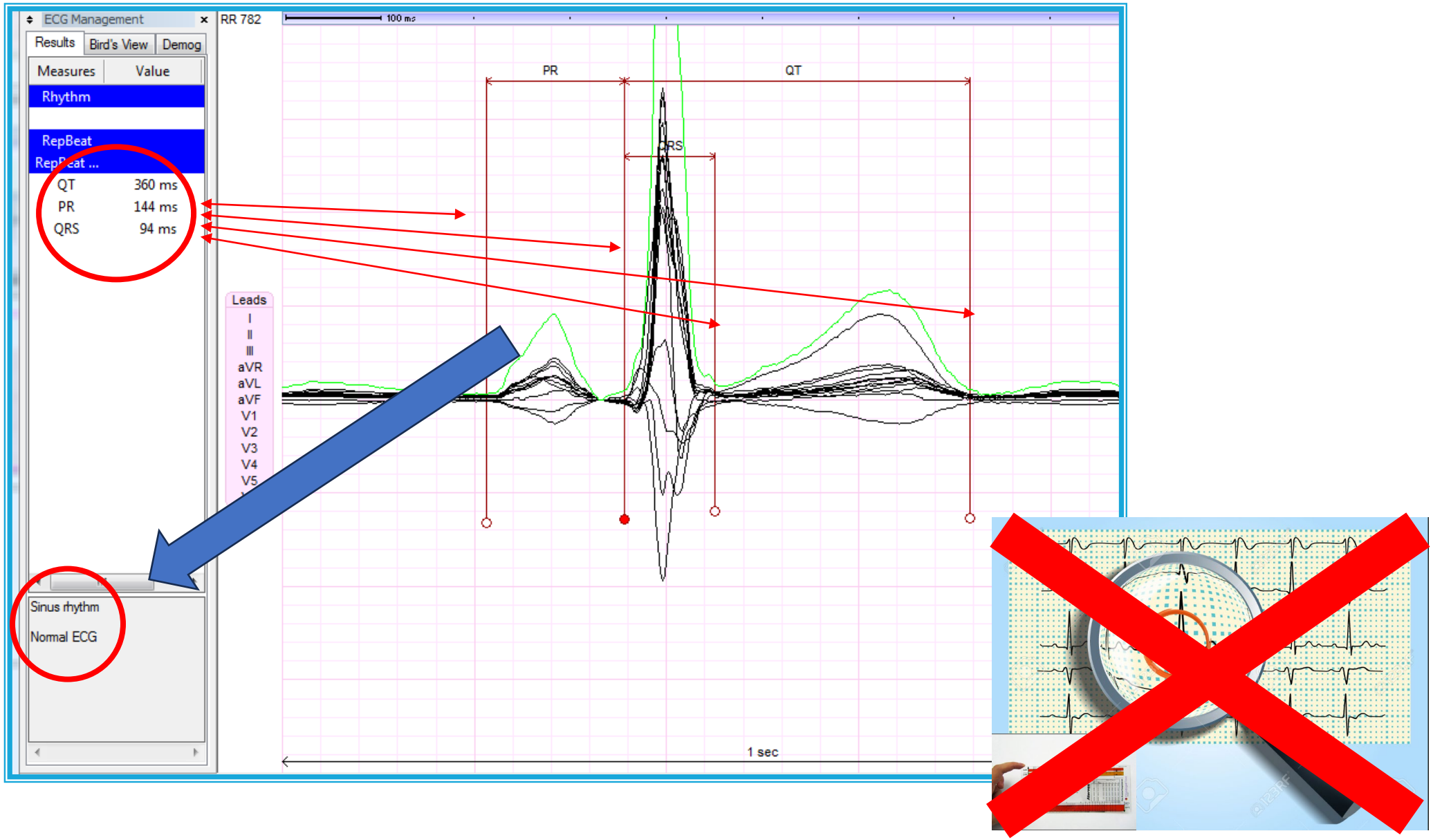
ECG digitale a 12 derivazioni

Time (ms)	Lead I (μV)	Lead II (μV)	Lead III (μV)	(other leads)	Lead V5 (μV)	Lead V6 (μV)
0	215	-61	-276	…	373	507
2	201	-97	-298	…	329	467
4	187	-133	-320	…	285	427
6	173	-169	-342	…	241	387
8	157	-205	-362	…	193	343
10	136	-236	-372	…	134	289
12	118	-249	-367	…	76	240
14	98	-263	-361	…	15	189
16	83	-268	-351	…	-46	132
18	71	-267	-338	…	-108	62
20	62	-262	-324	…	-152	5
22	54	-254	-308	…	-183	-50
24	46	-246	-292	…	-194	-83
…	…	…	…	…	…	…

colonna: single lead

riga: tutti i leads ad un tempo fisso

Misurare (ed interpretare) un ECG digitale



Recommendations for the Standardization and Interpretation of the Electrocardiogram

Part I: The Electrocardiogram and Its Technology

A Scientific Statement From the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society

Endorsed by the International Society for Computerized Electrocardiology

Paul Kligfield, MD, FAHA, FACC; Leonard S. Gettes, MD, FAHA, FACC; James J. Bailey, MD; Rory Childers, MD; Barbara J. Deal, MD, FACC; E. William Hancock, MD, FACC; Gerard van Herpen, MD, PhD; Jan A. Kors, PhD; Peter Macfarlane, DSc; David M. Mirvis, MD, FAHA; Olle Pahlm, MD, PhD; Pentti Rautaharju, MD, PhD; Galen S. Wagner, MD

Abstract—This statement examines the relation of the resting ECG to its technology. Its purpose is to foster understanding of how the modern ECG is derived and displayed and to establish standards that will improve the accuracy and usefulness of the ECG in practice. Derivation of representative waveforms and measurements based on global intervals are described. Special emphasis is placed on digital signal acquisition and computer-based signal processing, which provide automated measurements that lead to computer-generated diagnostic statements. Lead placement, recording methods, and waveform presentation are reviewed. Throughout the statement, recommendations for ECG standards are placed in context of the clinical implications of evolving ECG technology. (J Am Coll Cardiol 2007;49:1109–27)

Documento di consenso ANMCO/AIIC/SIT: Definizione, precisione e appropriatezza del segnale elettrocardiografico di elettrocardiografi, sistemi per ergometria, sistemi Holter ECG, telemetrie e monitor posto-letto

Michele Massimo Gulizia[1] (Coordinatore), Giancarlo Casolo[2] (Coordinatore), Guerrino Zuin[3] (Coordinatore), Loredana Morichelli[4], Giovanni Calcagnini[5], Vincenzo Ventimiglia[6], Federica Censi[5], Pasquale Caldarola[7], Giancarmine Russo[8], Lorenzo Leogrande[9], Gian Franco Gensini[10]

7.1 Elettrocardiografi

- Acquisizione ECG a 12 derivazioni simultanee.
- Banda passante del segnale ECG per tracciati a stampa e in memoria da 0.05 a 250 Hz con dimostrata funzionalità sui pazienti per tracciati di buona qualità.

Intelligenza artificiale e ECG

- **Che problema clinico si vuole risolvere?**
- **Quale modello implementare?**
- **Quali dati (e quanti dati) usare per addestrare il modello?**
- **Come viene/verrà fatto il labeling dei dati usati per l'addestramento?**
- **ECG «vero» (quanto meno digitale) oppure immagine?**
- **Quali metriche utilizzare per valutare l'accuratezza del modello**
- **L'output è una diagnosi oppure la misurazione di un parametro specifico (vedi intervallo QT)?**
- **Non sottovalutare MAI gli aspetti regolatori**

State of the Art of Artificial Intelligence in Clinical Electrophysiology in 2025: A Scientific Statement of the European Heart Rhythm Association (EHRA) of the ESC, the Heart

Methods and results

An AI checklist specific to EP was developed with expert input from the writing group and voted on using a modified Delphi process, leading to the development of a 29-item checklist. The checklist was subsequently applied to assess reporting practices to identify areas where improvements could be made and provide an overview of the state of the art in AI-related EP research in three domains from May 2021 until May 2024: atrial fibrillation (AF) management, sudden cardiac death (SCD), and EP lab applications. The EHRA AI checklist was applied to 31 studies in AF management, 18 studies in SCD, and 6 studies in EP lab applications. Results differed between the different domains, but in no domain reporting of a specific item exceeded 55% of included papers. Key areas such as trial registration, participant details, data handling, and training performance were underreported (<20%). The checklist application highlighted areas where reporting practices could be improved to promote clearer, more comprehensive AI research in EP.

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Perception Enhancement for Autonomous Vehicles in Foggy Conditions

Shimaa Ragab, Moustafa Elgendy, and Ahmed Shalaby[1].

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021-09637-z.

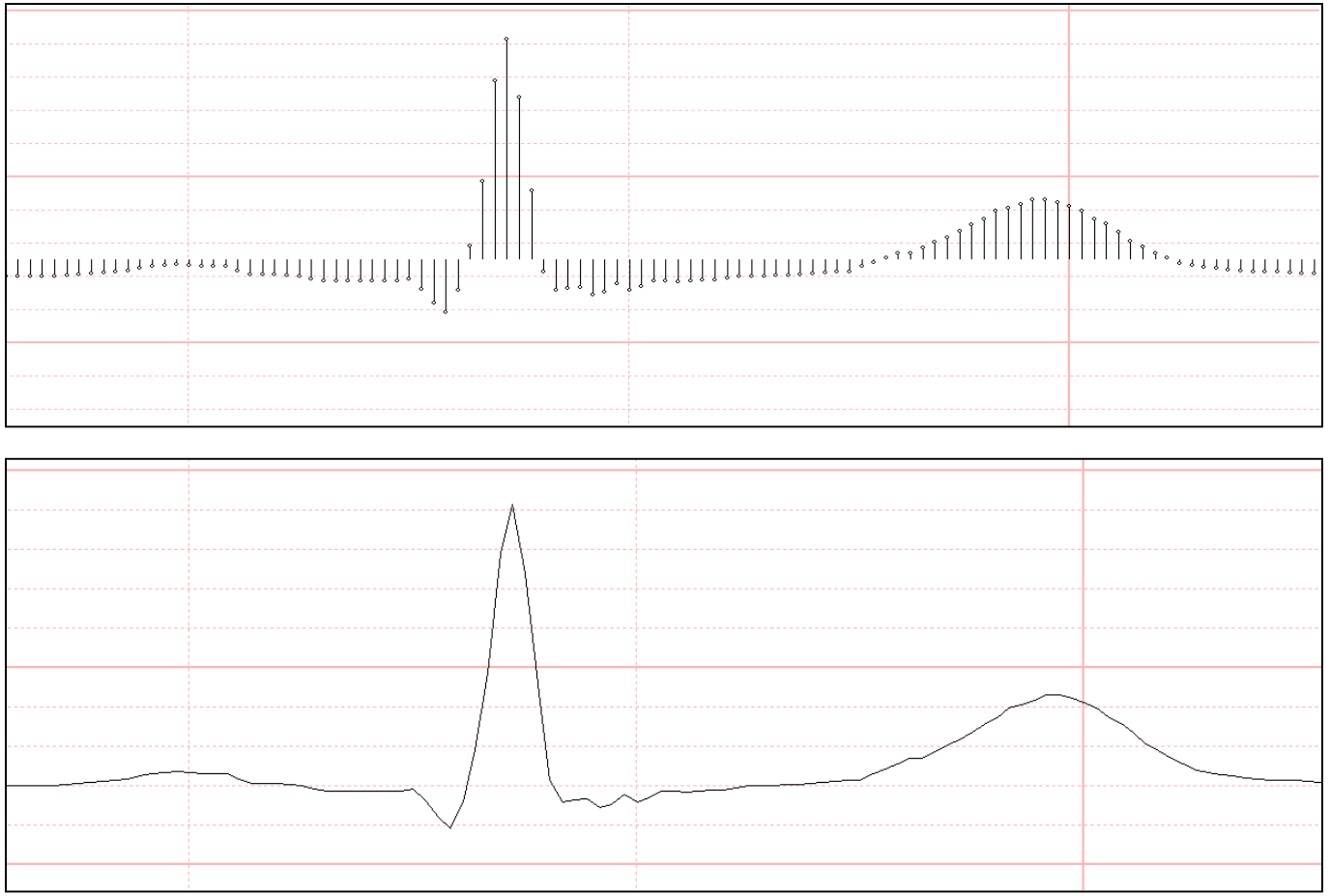
[43] M. Cordts *et al.*, "The cityscapes dataset," in *CVPR Workshop on the Future of Datasets in Vision*, 2015, vol. 2, p. 1.

[44] R. Sassi *et al.*, "PDF-ECG in clinical practice: A model for long-term preservation of digital 12-lead ECG data," *J Electrocardiol,* vol. 50, no. 6, pp. 776-780, Nov-Dec 2017, doi: 10.1016/j.jelectrocard.2017.08.001.

[45] Wang *et al.*, "Uct-dehaze: Towards real-world image dehazing via unsupervised contrastive learning," *IEEE Transactions on Image Processing,* 2024.

La Parola a Sassi

Disegnare un ECG digitale



EN 60601-2-51: «Se si usa il campionamento uniforme dei segnali ECG, i segnali ECG devono essere campionati con una frequenza di almeno 500 campioni/s per CANALE durante l'acquisizione dati. […] L'ampiezza quantificata deve essere ≤ 5 μV…….»

Identify confounding factors

Technology	Demographic	Diseases	Operator effect
• PPG: darker skin, temperature, sensing area, movement • ECG: electrode material/location, processing, movements, posture	• BMI, size, etc. • Ethnicity	• Impact on physiology • Similar manifestation on signal	• Placement accuracy • Manual selection, other operation actions

Use **knowledge** (literature, physiological mechanisms)
→ Analyse training data to identify additional confounders

Population biases

- Model performance:
  - Overall/total population performance is important
  - Subgroup performance is also important
- Source of biases:
  - Demographic, co-morbidities
  - Disease severity
  - Organizational (selection bias)
  - Equipment (e.g., ECG recorder)
  - Study design (e.g., invasive gold standard)

Validation data

Identify and validate all outputs

Representative and relevant:

- Ground truth
- Patient conditions, disease distribution

Beware of bias:

- Identify and mitigate potential bias
- Validation sites independent from training sites
- Geographic and organizational diversity

*Black-box algorithms are usually device-specific; agnostic claims require solid evidence

Evaluation metrics

Prioritary metrics

- Sensibility
- Specificity/PPV (adjust PPV for non-realistic prevalence)
- False-alarms rate (for bedside monitors, repeated spot-check, long-term monitoring, direct output to user)
- Confusion matrix

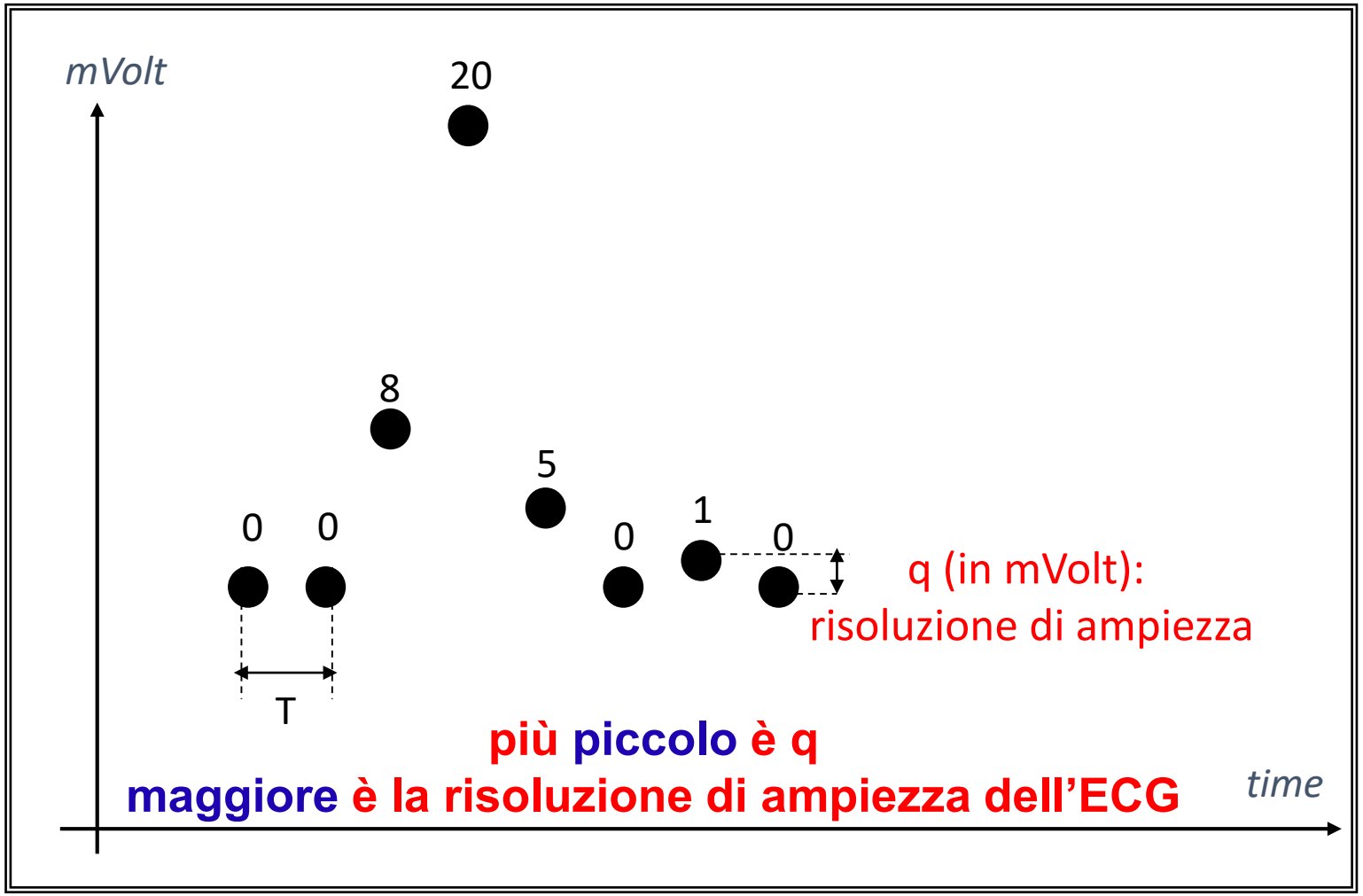
Less relevant metrics

- Negative predictive value
- F1-score
- ROC curves/AUC
- Qualitative analysis, “user preference”

Canovaccio

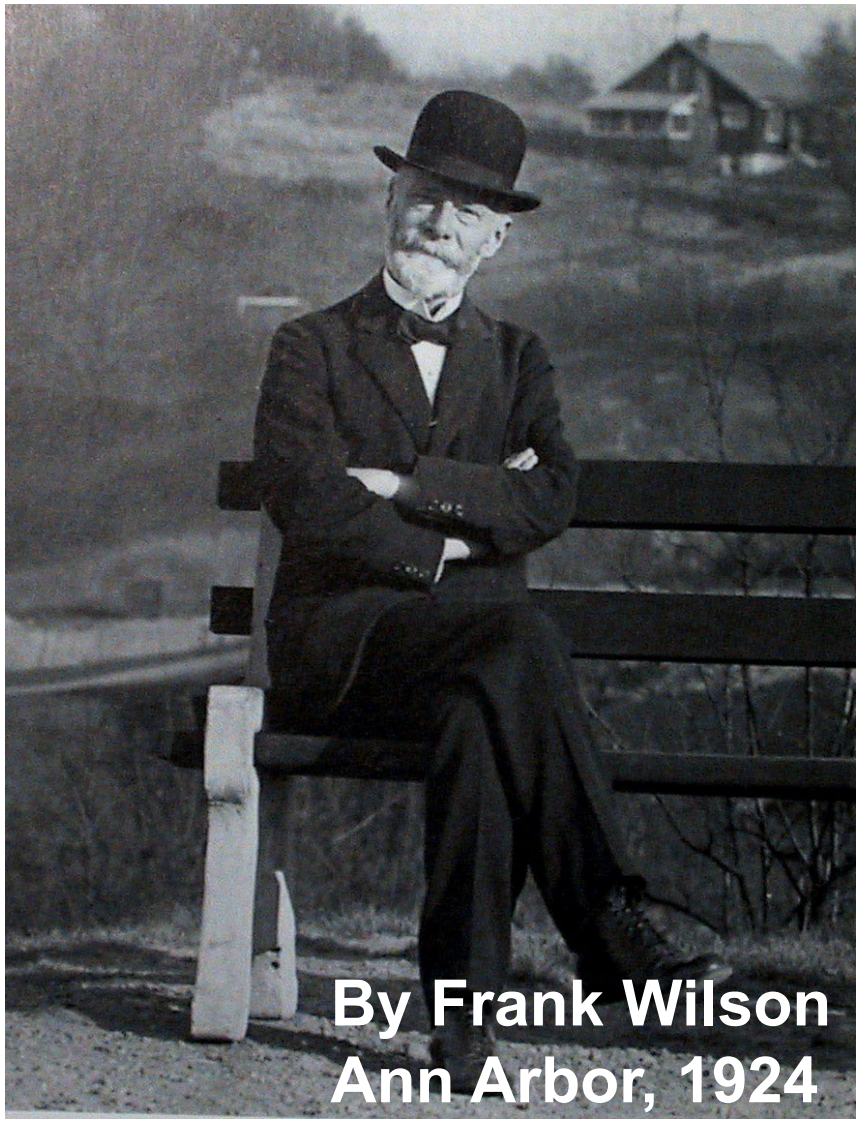
- Cenni storici sull'Elettrocardiogramma.
- Misurazione manuale dell'ECG
- Dall'ECG analogico all'ECG digitale (misurazioni automatiche)
- L'ECG diagnostico e l'interpretazione automatica
- La rivoluzione AI.
- Esempio su AF (comparazione rule-based versu ML).
- Aspetti regolatori
- Esperienza pharma (QT e altri parametri).

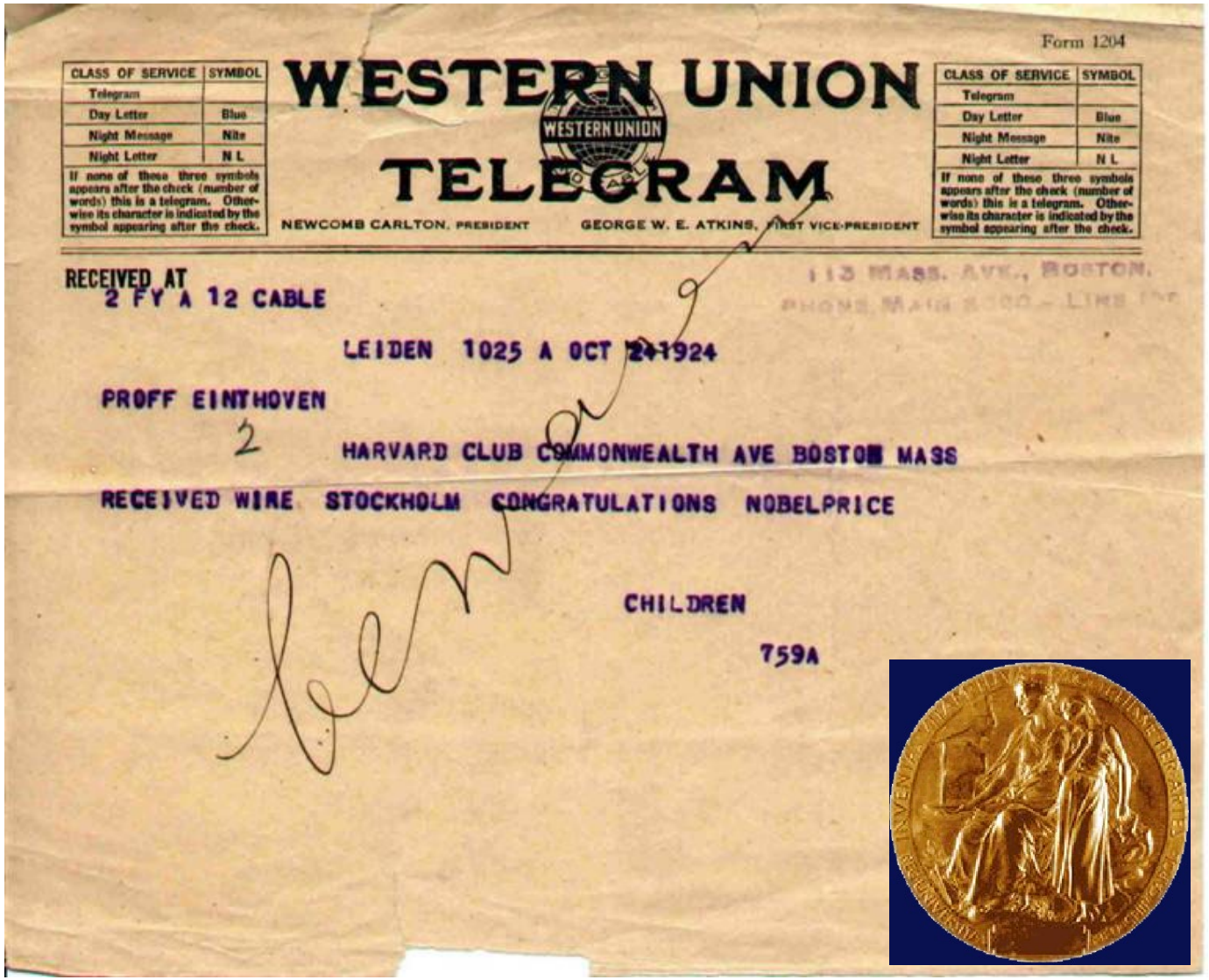
Risoluzione di Ampiezza



q = 50 microvolt (bassa risoluzione)
q = 5 microvolt (media risoluzione)
q = 1 microvolt (alta risoluzione)

PREMIO NOBEL PER LA MEDICINA 1924





Form 1204

CLASS OF SERVICE	SYMBOL
Telegram	
Day Letter	Blue
Night Message	Nite
Night Letter	N L

If none of these three symbols appears after the check (number of words) this is a telegram. Otherwise its character is indicated by the symbol appearing after the check.

WESTERN UNION

TELEGRAM

NEWCOMB CARLTON, PRESIDENT GEORGE W. E. ATKINS, FIRST VICE-PRESIDENT

CLASS OF SERVICE | SYMBOL
Telegram
Day Letter | Blue
Night Message | Nite
Night Letter | N L
If none of these three symbols appears after the check (number of words) this is a telegram. Otherwise its character is indicated by the symbol appearing after the check.

RECEIVED AT
2 FY A 12 CABLE

LEIDEN 1025 A OCT 24 1924

PROFF EINTHOVEN

2 HARVARD CLUB COMMONWEALTH AVE BOSTON MASS

RECEIVED WIRE STOCKHOLM CONGRATULATIONS NOBELPRICE

CHILDREN

759A